



The Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) Project Plan

by the Working Group on California Earthquake Probabilities (WGCEP)

Table of Contents

Introduction.....	3
Background	3
Implementation Plan	5
Epistemic Uncertainties and Logic Trees	5
Participants.....	5
Consensus Building.....	5
Coordination with NSHMP	6
Time Dependencies, Operational Aspects, and Potential Users.....	6
Contingency Plans	7
CEA Delivery Schedule.....	9
Main Model Components	10
Fault Models	10
Deformation Models	11
Earthquake Rate Models.....	12
Earthquake Probability Models:.....	14
Tasks	16
Planned Workshops & Review Meetings.....	22
References	24
Appendix – Detailed Task Descriptions	25
Task F1 - Update Faults.....	25
Task F2 – Reevaluate Fault Endpoints	27
Task D2 – B-Fault Bias.....	30
Task D3 – Line Integral Tools.....	30
Task R1 - Evaluate Along-Strike Distribution of Average Slip.....	32
Task R2 – Evaluate Magnitude-Scaling Relationships and Depth of Rupture.....	33
Task R3 - Paleoseismic Recurrence Interval Estimates	34
Task R4: Probability of Seeing Events in a Paleo Trench.....	37
Task R5: Solve the Large Inversion Problem.....	38
Task R6 - Fault-to-Fault Jumping Probabilities	40
Task R7 - Reassess Historical Earthquake Catalog	41
Task R8 - Reevaluate Earthquake Catalog	42
Task R9: Smoothed Seismicity Model	43
Task R10 – Mmax for off-fault seismicity	45
Task R11: Focal Mechanisms of Off-Fault Seismicity	46
Task R12 – Distribution of Repeated Slip at a Site on a Fault	48
Task R13 – Evaluate Physics Based Earthquake Simulators (for rate estimates)	48
Task R15 – Cascadia Subduction Zone.....	49
Task P1 – Address Empirical Model.....	50
Task P2 – ETAS explains Empirical Model?.....	51
Task P3 - Coulomb Stress Explains Empirical Model?	54
Tasks P5 & P6 - Implement ETAS for spatial-temporal clustering, and Evaluate Agnew-Jones	55
Task P8 - Evaluation Other Time Dependencies	57

Introduction

On June 25, 2009 the California Earthquake Authority (CEA) governing board approved \$2 million for the development of a Uniform California Earthquake Rupture Forecast, version 3 (UCERF3), and in late October 2009 they approved the final contract. The project started on January 1, 2010, and will last for 30 months.

Our primary goals with UCERF3 are to include multi-fault ruptures and spatiotemporal clustering. The latter will require robust interoperability with real-time seismicity information, and as such, UCERF3 will bring us into the realm of operational earthquake forecasting.

This document outlines anticipated issues in building UCERF3, and provides a research plan in the form of a list of tasks and planned workshops. The appendix here provides more details for those tasks that warrant further discussion at this time (and only if elaboration beyond what is given in the Task section below is in order). This plan is subject to change as the project evolves.

Background

On April 14, 2008, the *Working Group on California Earthquake Probabilities* (<http://www.WGCEP.org>) publicly released the *Uniform California Earthquake Rupture Forecast, version 2 (UCERF2)*. The development of this model was a joint effort between SCEC, the USGS, and CGS, with considerable support from the California Earthquake Authority (CEA), a provider of residential earthquake insurance. The main report, 16 appendices, executive summary, supplemental data, press release, and a fact sheet are all available at <http://www.SCEC.org/ucerf>.

Perhaps the most important accomplishment represented by UCERF2 was the development of a statewide model that uses consistent methodologies, data-handling standards, and uncertainty treatment in all regions. Also noteworthy is the coordination and consistency between UCERF2 and the model used in the 2008 [USGS national seismic hazard maps](#) (the latter using a time-independent version of UCERF2).

A more extensive analysis of the historical earthquake catalog in the development of UCERF2 revealed that the previous USGS national hazard map model (NSHMP, 2002) significantly over-predicts the rate of earthquakes near magnitude 6.5. This discrepancy was reduced to within the 95% confidence bounds of the observations by adjusting parameters in the UCERF2 model. However, most working-group participants believed that a better solution could be obtained by changing more fundamental aspects of the model. For example, the actual cause of the M 6.5 discrepancy may be the assumptions regarding fault segmentation and the lack of fault-to-fault ruptures. If true, then UCERF2 not only over predicts the probability of intermediate-sized events (near M 6.5), but also under predicts the frequency of larger ($M \geq 7$) earthquakes, which could have a significant impact on both hazard and loss estimates.

The working group identified the following shortcomings and/or issues with UCERF2 (which represents opportunities for improvement in UCERF3):

- **Interpretation of the “Empirical Model”** – WGCEP (2003) interpreted the apparent recent seismicity lull as a stress shadow cast by the great 1906 event, but the fact that most of the state exhibits an apparent lull calls this interpretation into question. This issue represents the single largest epistemic uncertainty for time-dependent probabilities in UCERF2.
- **Relax Segmentation & Include Fault-to-Fault ruptures** – Fault-to-fault ruptures, like the 2002 Denali earthquake, are not included in UCERF2. As discussed above, their inclusion might solve our remaining M 6.5 over prediction (and a likely M \geq 7 under prediction).
- **Self-consistent, Elastic-Rebound-Theory Motivated Renewal Models** – Inclusion of multi-segment ruptures, or relaxing segmentation altogether, introduces as-yet unresolved conceptual problems in computing conditional time-dependent probabilities.
- **Include Earthquake Triggering and Clustering** – UCERF2 does not include any type of triggering (e.g., as caused by static or dynamic stress changes, or as represented by aftershock statistics). Some believe that these effects are more important than the time dependence presently included in UCERF2, especially if a moderate or large event were to occur.
- **Extent of Earthquake Ruptures with Depth** – Both state-of-the-art earthquake forecast models (like UCERF2) and ground-motion simulations (like SCEC’s CyberShake) depend heavily on magnitude-area relationships, and those currently available have big and important differences that must be resolved with respect to the depth extent of large ruptures (e.g., UCERF2 and CyberShake use incompatible models). Closely related to this are the quantification of seismogenic depth, aseismicity, and coupling coefficients (and the magnitude dependence of these).

All of the above issues are discussed extensively in the UCERF2 report. Each of these problems motivates aspects of the UCERF3 plan presented here.

Much effort in building UCERF2 was put into developing a computational infrastructure that is both modular (object-oriented) and extensible to UCERF3 ([click "Model Framework" at http://www.WGCEP.org](http://www.WGCEP.org)). We also developed distributed and electronically accessible data resources ([click "Data" at http://www.WGCEP.org](http://www.WGCEP.org)) as well as analysis tools based on open-source software (e.g., <http://www.OpenSHA.org>). In short, we have developed an extensive and extensible IT infrastructure upon which we can build, which will save much time and money compared to starting from scratch.

Implementation Plan

Epistemic Uncertainties and Logic Trees

Because there will be no single consensus model for UCERF3, it will be important that the modeling framework adequately represent epistemic uncertainties (our lack of understanding of how nature works, as opposed to “aleatory” uncertainty which represents the inherent randomness assumed in a given model). As with UCERF2, we anticipate representing epistemic uncertainties in UCERF3 using logic-tree branches that account for multiple models constructed under different assumptions and constraints.

Participants

The WGCEP organizational structure used for UCERF2 development will be maintained for UCERF3; it comprises an Executive Committee (ExCom), a Management Oversight Committee (MOC), and a Scientific Review Panel (SRP) (see ["Participants at http://www.WGCEP.org](http://www.WGCEP.org) for current members). Other WGCEP participants include research scientists, resource experts, model advocates, and IT professionals.

The ExCom is responsible for convening experts, reviewing options and making decisions about model components, and orchestrating implementation of the model and supporting databases. One role of the ExCom is to ensure that the models incorporated into UCERF3 span the range of model viability. The MOC is in charge of resource allocation and approving project plans, budgets, and schedules; it is also responsible for seeing that the models are properly reviewed and delivered. The SRP is an independent body of experts that will review the development plans and model elements; in particular, they will evaluate whether the WGCEP has considered an adequate range of models to represent epistemic uncertainties. The SRP is participatory in the sense that it was convened at the very beginning of the project and will serve throughout the project period

It's important to note that the separation of these roles will not always be maintained in an absolute sense. For example, given their expertise or experience, an SRP member may at times play an advocacy role with respect to a given model component. In such circumstances it will be important to identify which “hat” a participant is wearing. In general, the SRP to keep the ExCom in check with respect to any such conflicts of interest, and the MOC will keep the SRP in check.

Consensus Building

Discussion of model options and consensus building will be achieved through a series of community workshops described in the preliminary schedule outlined below. These workshops will include participants from the broader community in order to ensure views that go beyond the active WGCEP participants. Some workshops will focus on the scientific ingredients going into UCERF3, while others will be aimed at informing and/or getting feedback from user communities.

Decisions with respect to logic-tree branches and weights are the responsibility of the ExCom. The ExCom must also provide the scientific rationale for why the models were selected and how the weights were assigned. The SRP will review the ExCom decisions. Interactions between the ExCom and SRP will be mediated by the MOC.

While the ExCom will likely need to rely on expert opinion in establishing some logic-tree branch weights, it is our explicit goal to base these decisions on criteria that are as quantitative, reproducible, and testable as possible. Take the likelihood of a rupture jumping from one fault to another as an example. Ideally we would have a formula that provides a jumping probability as a function of fault separation, relative geometry, sense of slip, slip rates, hypocenter, etc. Because no such formula yet exists, however, we may instead be forced to rely on expert judgment based on a case-by-case analysis of each neighboring fault combination in California. Clearly, a formula giving a fault jumping probability is more testable than relatively subjective expert opinion, as the former could be formally tested against events occurring worldwide. This is not to denigrate expert opinion however, as it can be a powerful way of assimilating complex information on how nature operates.

Coordination with NSHMP

As with UCERF2, UCERF3 is being developed in full cooperation and coordination with the USGS National Seismic Hazard Mapping Program. It is WGCEP's goal that the time-independent version of UCERF3 be used for the next round of USGS hazard maps for California, which are scheduled for release circa 2013. Coordination will be facilitated by Ned Field's dual role as WGCEP chair and as USGS lead for the California part of the NSHMP forecast model.

Time Dependencies, Operational Aspects, and Potential Users

A particularly ambitious aspect of UCERF3 is to develop an operational earthquake forecast—an authoritative model that can be revised in near real time as significant events unfold. (Here “significant” means events that significantly modify estimates of subsequent earthquake probabilities.) WGCEP's goal is to construct a model that will produce forecasts across a wide range of time scales, from short term (days to weeks), through intermediate term (e.g., annual forecasts), to long term (decades to centuries). Short-term forecasts could be used, for example, to alert emergency officials of the increased hazard due to a moderate-sized earthquake occurring near a fault that is considered close to failure. Yearly forecasts could be used by homeowners to decide whether to buy earthquake insurance for the following year, or by those needing to price insurance premiums or catastrophe bonds. Long-term forecasts could (and do) influence building codes.

Obtaining a full range of forecasts from a unified model would be an improvement over current practice in which the short-term and long-term forecasts are derived almost independently. This is because there are significant dependencies between the parameters that control the results at different time scales. For instance, in an Epidemic Type Aftershock Sequence (ETAS) model, the long-term probabilities represented by the background rate of events trade off against the aftershock productivity parameters that control the short-term probabilities. Also, while aftershock sequences are generally considered to be a short-term phenomena, it has been

demonstrated that they can produce significant probability changes over periods of years to decades. By considering all time dependencies within one model framework, we will be able to develop a consistent set of forecasts.

The utility of UCERF3 will be dictated by not only what the user community is interested in applying, but also by the confidence we have in the forecast given uncertainties. Therefore, it will be important to have an ongoing dialogue between potential users and model developers throughout the duration of the project. This will help to clarify both their needs and our ability to deliver something meaningful given present knowledge. Use in earthquake insurance will certainly be a priority given CEA's financial support. However, there are other potential uses as well, like as a resource to help the California and/or National Earthquake Prediction Evaluation Councils advise on earthquake threats following significant events. The USGS currently makes short-term forecasts during earthquake clusters with users including the California Emergency Management Agency, other emergency responders, and utilities. Our operational model will improve these short-term forecasts by making them consistent with the long-term model.

It is also important to note that perceived needs of the user community should not be the sole driver of our priorities. The USGS ShakeMaps are a good example of a product whose usefulness was not fully anticipated in advance. In fact, until we have both a time-dependent, operational model *and* the tools with which to explore loss implications, no one will really know what's important for users. This again emphasizes the need for ongoing dialogue from the very beginning.

Feedback from potential users may very well focus our efforts on either shorter-term or longer-term time dependencies. Our scientific understanding may also point us in a particular direction, as we would not want to spend a lot of time building a model with such large uncertainties that it's rendered useless. That being said, there are also good scientific reasons for attempting to construct a "broadband" time-dependent model. As discussed above, there is not a physically meaningful division between short-term and long-term forecasts, and attempting to draw such a line may present more problems than it solves. Another is that there's no better way to highlight the important, deeper scientific issues than to actually attempt to build a system-level model. An example of such a question in the context of our present goals is "what's the difference between a multi-fault rupture and a separate earthquake that happened to be triggered quickly?" Attempting to build a broadband model will be scientifically healthy and thereby stimulate overall progress.

Finally, it's important to emphasize that we endeavor to build a model that *could* be used in an operational sense. This should not be interpreted as a commitment or promise to build a model that *will* be maintained operationally, as we do not yet know the feasibility or what resources will be required for such ongoing maintenance (let alone the full scope of legal issues).

Contingency Plans

As with any ambitious project, it is possible that not all goals will be achieved by the final delivery date. (Previous WGCEP efforts have repeatedly reinforced the truthfulness of "it's easier said than done" and "the devil is in the details".) In the worst case, the WGCEP may conclude that the best available science has not yet provided a representation of multi-fault

ruptures and/or spatial-temporal clustering that is adequate for operational purposes. A project plan has been developed to deal with these uncertainties. In particular, the UCERF3 logic-tree structure will be capable of handling this situation by using model branches developed for UCERF2 as appropriate fallbacks.

CEA Delivery Schedule

June 30, 2010 - Methodology Assessment – Issues and Research Plan (Report #1)

Written report summarizing the status of the model components, a research plan for addressing outstanding questions and issues, and a preliminary implementation plan for the UCERF3 model. Report will provide details broken out by the main model components and/or by task, as deemed appropriate.

December 31, 2010 - Methodology Assessment – Proposed Solutions to Issues (Report #2)

Written report summarizing proposed solutions to the questions and issues identified in Report #1, and a revised implementation plan for the UCERF3 model. Report will provide details broken out by the main model components and/or by task, as deemed appropriate.

May 31, 2011 - Proposed UCERF3 Plan (Report #3)

Written report by WGCEP summarizing the proposed implementation plan for the UCERF3 model. This report will identify the remaining implementation issues requiring short-term, targeted research.

June 30, 2011 - SRP Review of Proposed UCERF3 Plan (Report #4)

Written report by the SRP that reviews the proposed UCERF3 implementation plan and recommends modifications.

September 30, 2011 - Final UCERF3 Plan (Report #5)

Written report by WGCEP that responds to the SRP review (as well as reviews by NEPEC, CEPEC, and CEA), provides a final implementation plan for the UCERF3 model, and summarizes progress towards implementation.

March 31, 2012 - Preliminary UCERF3 Model (Report #6)

Preliminary version of the UCERF3 model by WGCEP, implemented on the OpenSHA computational platform and documented in a written report.

April 30, 2012 - Review of Preliminary UCERF3 Model (Report #7)

Written report by the SRP that reviews the preliminary UCERF3 model and documentation and recommends modifications.

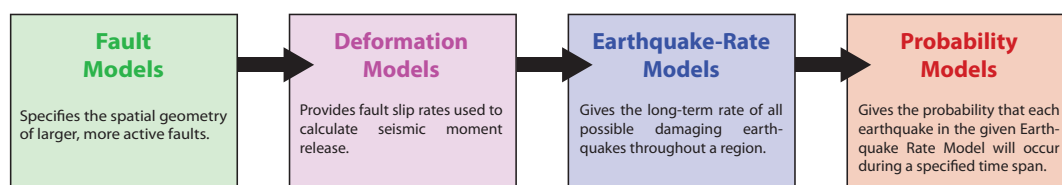
June 30, 2012 - Final UCERF3 Model (Report #8)

Final version of the UCERF3 model by WGCEP, implemented on the OpenSHA computational platform and documented in a written report. This final report will also include recommendations to CEA on the use of UCERF3, as appropriate, and recommendations on how UCERF3 can be improved by further research and development.

Main Model Components

As with UCERF2, UCERF3 will be constructed from the four main model components shown and defined in Figure 1. We acknowledge that dividing any complex interactive system into separate components has some degree of artificiality and arbitrariness. Nevertheless, we believe those established here are both meaningful and necessary, at least for the time being. Where the distinction may become problematic is between the Earthquake Rate and Probability models. All previous WGCEP and NSHMP forecast models have first defined the long-term rate of each event, which does have both physical meaning (in terms of being conceivably measurable) and practical use (e.g., in current building codes). However, drawing this distinction can become problematic when constructing a model. For instance, and to reiterate the example given above, how will we differentiate between the rate of a particular multi-fault rupture and the probability that one fault might quickly trigger another as a separate event? Furthermore, physics-based earthquake simulators, which are discussed more below, do not make any modeling distinction between an earthquake rate and a probability component (although one may still need to infer long-term rates in order to apply the results). Therefore, the distinction between Earthquake Rate and Probability models in what follows may dissolve at some point as UCERF3 is developed.

Figure 1. Main Components of the UCERFs 2 & 3



Fault Models

Fault models give the spatial geometry of the larger, known, and active faults throughout the region, with alternative models representing epistemic uncertainties. For UCERF3 we will update and revise those developed for UCERF2 (going from fault model versions 2.1 and 2.2 to versions 3.x). Tasks here will include adding new faults and/or modifying existing ones based on recent studies (e.g., from the PG&E supported work in central Ca.). There is also the possibility that some faults will be removed if their existence is no longer suspected. Coordination and consistency with the planned, statewide “community fault model” under development in SCEC is important, as is the inclusion of faults that lack geologic slip-rate constraints because the deformation models discussed below may provide such estimates.

Because one of the goals in UCERF3 is to include multi-fault ruptures, reconsideration of fault endpoints will also be important, especially since most faults were not originally mapped with this issue in mind. Just how well do we know the proximity of neighboring faults, and what information can we gather to improve this understanding? Exactly how do we quantify and represent such uncertainties in our database? Because endless resources could be poured into

this question, we'll need to consider cost versus benefits in determining an appropriate level of effort.

Deformation Models

Each deformation model gives a slip-rate estimate for each fault section in the fault model, plus deformation rates off the explicitly modeled faults (specified as slip rates in polygons in Deformation Models 2.x). For UCERF3 we will be updating Deformation Models 2.x with versions 3.x. The values assigned in previous models have been based on expert-opinion evaluation of available data (mostly geologic and geodetic), together with summations across various transects to make sure the total plate tectonic rate is matched.

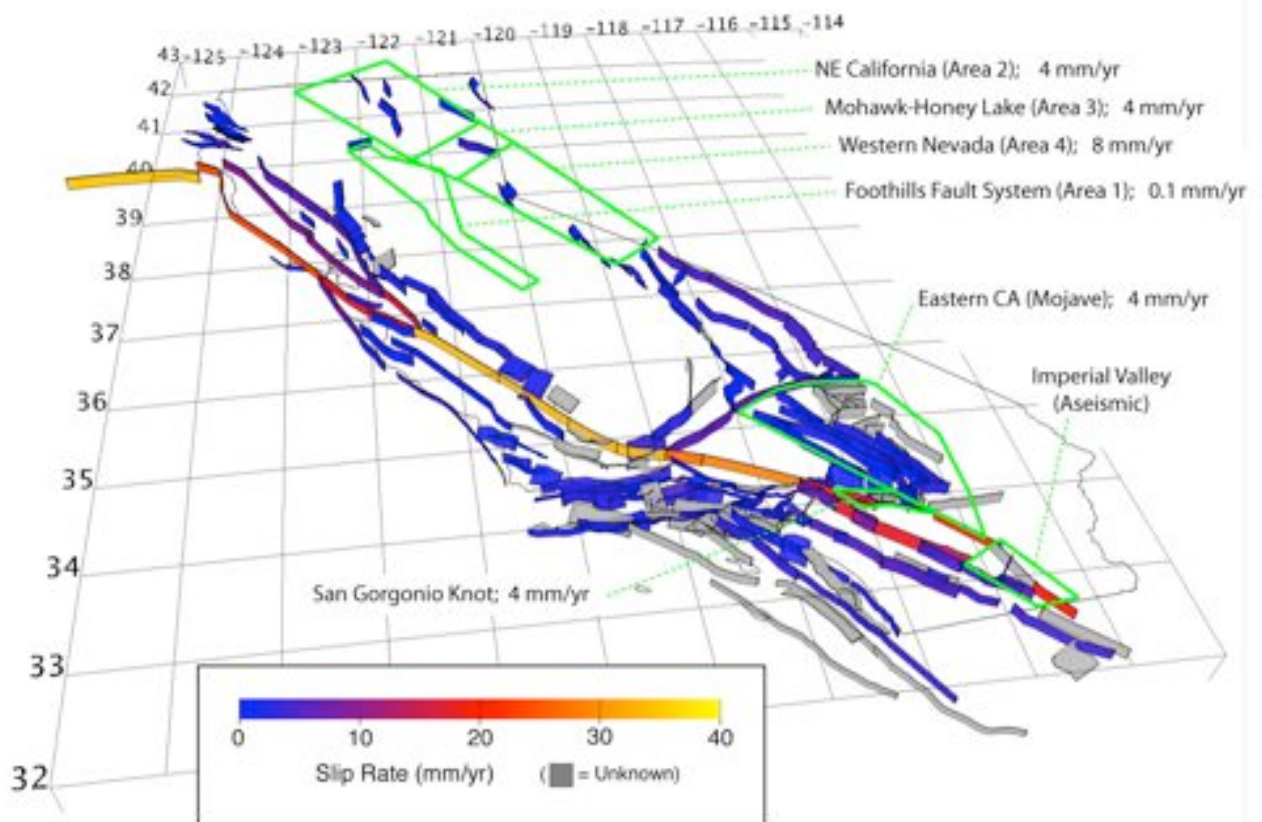


Figure 2. Faults and slip rates for Deformation Model 2.1, plus the polygons (green) representing significant deformation elsewhere in the region.

One big question is whether more quantitative models, such as Peter Bird's NeoKinema (e.g., Bird, 2009), can be used in place of expert opinion (the topic of a [SCEC workshop on April 1-2, 2010](#)). The other big questions here include:

- Can the more sophisticated deformation models give us slip rate estimates for the faults where we currently lack geologic constraints (e.g., those plotted in gray in Figure 2).
- Can these deformation models give us a more refined estimate of the *spatial distribution* of deformation occurring off the explicitly modeled faults (something better than the polygons defined for the last model)? This would provide a good alternative to smoothed instrumental seismicity for constraining the rate or maximum magnitude of "background" seismicity (earthquakes off the explicitly modeled faults).
- Related to the above is the overall amount of seismic deformation occurring off the explicitly modeled faults. Deformation Models 2.x were constructed to explicitly match the total plate rates (within uncertainties), which basically assumed that all seismic deformation occurs on the modeled faults (i.e., assuming rigid blocks in between). One question is whether we should reduce such fault slip rates by some fraction in order to avoid double counting with respect to off-fault seismic deformation. In fact, NeoKinema suggests that the off-fault deformation is 30% (which implies we may have over-estimated some fault slip rates).
- Can we get a more refined estimate of slip-rate changes along strike (i.e., to avoid unphysical abrupt changes at the current fault-section boundaries. An alternative here would be to assign existing slip rate constraints only at section midpoints (unless an abrupt change is expected due to fault branching). However, exactly how and if slip tapers off between neighboring faults will likely be very influential in solving for the rate of multi-fault ruptures, so we probably need to address such transitions in as much detail as possible.
- Is there a systematic bias in the assignment of slip-rates to some of the slower moving faults (e.g., by implicitly defining a water level)?

Finally, it will be important to have a range of deformation models in order to represent uncertainties with respect to the above issues (versions 3.1, 3.2, ...).

Earthquake Rate Models

The goal here is to define the long-term rate of all possible earthquake ruptures (above some magnitude threshold and at some discretization level that is sufficient to capture hazard). As stated above, our primary aim with UCERF3 is to relax segmentation and include multi-fault ruptures. Note that relaxing segmentation does not necessarily mean removing it, but rather sampling the range of models that are consistent with the data (which may or may not exhibit segmentation). In addition to the physics-based simulators (discussed below), we currently have three distinct approaches being pursued; one by Morgan Page and Ned Field (e.g., Field and Page, 2010); one by Tom Parsons (Parsons and Geist, 2009); and one by David Jackson. Details of each are beyond the scope here, and the exact anticipated implementations are evolving

rapidly and some approaches may merge together. Suffice it to say that all the current techniques require most of the following ingredients:

- Faults with slip-rate estimates (from the Deformation Model).
- Spatial distribution and total amount of seismic deformation occurring off the explicitly modeled faults (from the Deformation Model).
- Paleoseismic event-rate estimates, plus the probability that events of various magnitudes may go undetected in a trench.
- Fault-to-fault jumping probabilities (relative to the likelihood of through-going rupture if there were no separation, no change in strike or faulting style, or no change in whatever metric is used to define the probabilities). What's needed here is a review of the literature (both observational and theoretical), a recommended applicable model based on this review, and a research agenda for making further progress. One issue is the fact that empirical studies were conducted after given earthquakes, as opposed to being based on the more uncertain information we have before events. Another question is how we quantify and utilize uncertainties in fault endpoints? Finally, do we develop testable generic rules or do we consider each possible connection in our fault model on a case-by-case basis.
- Magnitude-scaling relationships (mag versus area, mag versus length, slip versus length and/or a model of average slip as a function of depth and magnitude) The main question is whether rupture depth for larger events continues to increase with magnitude (or whether it's limited by the depth of microseismicity). Of consideration here should be kinematic inversion results, implications of dynamic rupture modeling, and observed seismicity. We need a range of viable models to represent existing uncertainties. Ideally each would provide a model giving average slip as a function of depth and magnitude, together with a mutually consistent set of mag-area, mag-length, and slip-length relationships (where the latter is slip at a depth of ~6 km rather than an average over the entire depth range). This will also require mutually consistent definitions of upper and lower seismogenic depth, aseismicity factor, and coupling coefficient (to the extent these parameters remain relevant).
- Model(s) giving average slip as a function of position along rupture (averaged over many occurrences of the exact same event). Does the tapered model (square root of \sin) applied in UCERF2 hold up given recent events? Does it apply to multi-fault ruptures? What about multi-fault ruptures with a change in the style of faulting?
- Smoothed instrumental seismicity (to get at the spatial distribution of a-values). This should perhaps include lower magnitudes and involve applying tighter smoothing given RELM test results and precarious-rock constraints.
- Probability of different focal mechanisms as a function of space for background seismicity.
- Maximum magnitude for background seismicity as a function of space.

- Total magnitude-frequency distribution estimate of the entire region.
- Total magnitude-frequency distribution for background seismicity (i.e., off the explicitly modeled faults).
- A more mutually consistent way of merging gridded seismicity with fault-based rates (to avoid the step functions in incremental magnitude-frequency distributions of some areas).

The current working group has expressed the desire that new earthquake-rate models be constructed using well-defined, objective rules. As discussed above, two important reasons for this are increased reproducibility and testability.

Physics-based earthquake simulators represent a viable way of developing an earthquake rate model (e.g., run them for a very long time and look at the rate of each rupture). These are particularly appealing in that they naturally relax segmentation and include multi-fault ruptures. However, the question remains whether these models reliably capture the relevant earthquake physics, and whether their usefulness is diminished by producing a wide range of behaviors among the different simulators (or for alternative parameter settings within a given simulator). At the very least physics-based simulators will be useful exploratory tools, and we plan to use them as such. Fortunately SCEC has a formal working group dedicated to the development, verification, and evaluation of these models, and we are actively working with that group in order to utilize simulators to the maximum extent possible. This group is being led by Terry Tullis, and the leaders of the groups developing different simulators that might be applicable statewide include:

- John Rundle (*Virtual California*; Rundle et al, 2006)
- Steve Ward (*ALLCAL*; Ward, 2000)
- James Dieterich (*RSQSim*; Dieterich and Richards-Dinger, 2010)
- Fred Pollitz (*VISCO-SIM*)

Earthquake Probability Models:

The earthquake probability models give the probability that any one of the events in the earthquake rate model will occur over a specified time span (using, for example, information on the date of the last event). Our main goals here for UCERF3 are the following:

Resolve Interpretation of Empirical Model

This will involve 1) further assessment of historical earthquake catalog (including how we get from felt reports to intensity estimates to magnitude/location); 2) further catalog analysis and interpretation (e.g., are inferred rate changes sensitive to polygon definitions?); 3) evaluation of whether ETAS can explain the observed rate changes, especially given known events; and 4) examination of whether static coulomb stress-change models can explain the observations.

Develop Self-Consistent Elastic Rebound Models

This will include exploring physics-based simulator results to look for relatively simple statistical relationships (like the average time-predictable model Ned Field has presented). This gets at the question of how we might use simulator results (which isn't clear even if we assume one is exactly correct). Of course we don't know whether any simulator is correct, so it will be important to test any such statistical behavior for robustness against the range of simulator results, as well as against actual observations to the extent possible.

Apply Spatial-Temporal Clustering Models

Our first order application will be a simple ETAS model where the triggered events will be sampled from the long-term rate model (so that magnitude 8 events can only be triggered where such events can occur in the long-term model). This does not limit large earthquakes to known past events but to faults or source regions where the long-term model allows such events to occur in the future. Questions here include: 1) will we need to compute spatially variable ETAS parameters to reflect the fact that the long-term magnitude-frequency distribution is spatially variable (and perhaps non Gutenberg Richter)?; 2) should we follow the current practice of the STEP model and compute temporally variable or sequence specific parameters, or is the range of variability consistent with a single set of ETAS parameters?; 3) what should the lower magnitude limit be for updating the forecast based on observed seismicity?; 4) is the fraction of main shocks versus triggered events magnitude dependent? Our strategy will be to start with the simplest model and add complexity as needed to satisfy data or other constraints. Parallel efforts will look at the usability and relative implications of static stress-change models and the Agnew and Jones (1991) foreshock-statistics methodology.

Evaluate Physics-Based Earthquake Simulators

We also want to explore the possible use of physics-based simulators. It appears doubtful that any one simulator will be applicable for direct forecasting purposes because it is not clear how to use the results even if you assume they are perfectly correct. The evaluation of simulators is clearly a longer-term effort. For now we will use them at least as exploratory tools, and perhaps as a means to constrain some of the parameters applied in our more statistical-based approaches (to examine recurrence interval probability distributions and/or magnitude-frequency distributions on faults or in regions). This would be analogous to using 3D waveform simulations to constrain the functional form of empirical ground motion attenuation relationships.

Tasks

In keeping with our [Model Framework](#), our tasks can be separated into those associated with the Fault Model(s), Deformation Model(s), Earthquake Rate Model(s), and Earthquake Probability Model(s). The following table lists the various tasks currently envisioned for each of these components, as well as tasks associated with the “Implementation”. Potential participants are also listed, with the primary contact/leaders shown in **Bold**. Those tasks that warrant further discussion at this point are described in the appendix (but only if further discussion is in order at this time).

It should be noted that these tasks are likely to change as the project evolves (some may be removed and some may be added). It is also difficult to associate some tasks with only one model component (e.g., the task for the empirical model could have been put under the Earthquake Rate rather than Probability component).

Notes: **USGS Western Region participants are listed in red**, and **USGS Central Region participants are listed in Blue** (not including Jones or Parsons). While the task leaders are pretty well established, **some of the participants are somewhat speculative at this point**, and others may be added.

	Task	Description	Leader & Participants
Fault Model(s)	F1) Update Faults	a) Revise or add any new, important faults (even if slip rates are not well constrained because deformation modeling might help define these). This should include results from PG&E supported work and should be coordinated with the SCEC statewide community fault model development. <i>See appendix for further discussion of this task.</i>	Dawson, J. Shaw, Wills, Weldon, Haller , Grant, Powers , , Parsons , and Murray .
	F2) Reevaluate Fault Endpoints	b) Reconsideration of fault endpoints given importance of this for multi-fault ruptures Endpoints should be evaluated using a synthesis of available geologic, geophysical, and seismological data and this uncertainty will be characterized in the fault database. <i>See appendix for further discussion of this task.</i>	Dawson , Parsons , Powers , J. Shaw, Plesch, L. Grant, A. Michael
	F3) Database Issues	d) Decide the future of the California Reference Fault Parameter Database . We certainly need the Fault-Section Database (versions 3), but the need for the Paleo Sites Database is debatable (from a cost benefit perspective), especially since what we will really use is an update of Tom Parsons’ paleoseismic recurrence-interval estimates (Appendix C or UCERF2). We also need to determine how this database will relate the both the NSHMP database and the forthcoming GEM database.	Field , Weldon, Haller , Petersen , Dawson, Wills, Jordan, McCarthy , Powers , Biasi, Parsons
	F4) Compile Slip in Last Event Data	g) Gather data on slip in last event along faults where this can be obtained (i.e., for application of the average time-predictable model). Utilize LiDAR for this purpose? How and where should this be stored?	Weldon , Biasi, Hudnut (the latter for LiDAR?)

	Task	Description	Leader & Participants
Deformation Model(s)	D1) Evaluate New Deformation Models	<p>Develop a new set of deformation models based on the more sophisticated modeling approaches that have recently emerged (e.g., NeoKinema, Harvard-MIT block model, Shen/Zeng model, Parsons' 3D FE model). These models will include both slip rates on our explicitly modeled faults, as well as deformation rates elsewhere if possible (where the latter could be used as an alternative constraint on the rates or maximum magnitudes of "background" seismicity). A range of models will be given in order to represent epistemic uncertainties. The following are some of the other questions that this task will try to address:</p> <ol style="list-style-type: none"> 1) What is the fraction of "off-fault" deformation? Can each model be very specific about what amount of the deformation contributes to slip rates inferred from paleoseismic studies versus what amount is manifested as nearby off-fault earthquakes? 2) Do we need to compile purely geologic slip-rate constraints for these deformation models? 3) Can we constrain slip rates on those faults that have no geologic information? 4) Can we differentiate slip rates on closely spaced faults? 5) Can we constrain slip rate variations along strike (since how slip tapers at the ends of faults could be very important in terms of multi-fault rupture likelihoods)? 6) Can we use GPS to help constrain the distribution of aseismicity and seismogenic depths (the latter being related to locking depths)? 7) What are the long-term after effects of previous large earthquakes (like those in 1857, 1872, and 1906)? <p><i>See the report from the April 1-2, 201 Workshop for more information.</i></p>	Thatcher , Zeng , Hearn, Johnson, and Sandwell.
	D2) B-fault bias?	e) Evaluate whether B-fault geologic slip rates are biased (always rounded up, or always given some minimum/default value?).	Weldon , Dawson
	D3) Line integral tools	f) Implement tools for line-integral testing (Parsons has started this); strain tensor analysis tools for polygons applied to deformation or earthquake-rate models. Vertical components could be an important additional constraint.	Parsons , Milner, Powers, Weldon

	Task	Description	Leader & Participants
Earthquake Rate Model(s)	R1) Evaluate Along-Strike Distribution of Average Slip	What is the average along-strike distribution of slip in an earthquake, especially when multiple faults are involved (e.g., reduce slip at the connections)? What if the style of faulting changes between faults? <i>See appendix for further discussion of this task.</i>	Biasi , Weldon, Dawson, & Wesnousky?.
	R2) Evaluate Magnitude-Scaling Relationships and Depth of Rupture	Resolve discrepancies in existing magnitude scaling relationships. The main question is whether rupture depth for larger events continues to increase with magnitude (or whether it's limited by the depth of microseismicity). Of consideration here should be kinematic inversion results, implications of dynamic rupture modeling, and observed seismicity. We need a range of viable models to represent existing uncertainties. Ideally each would provide average slip as a function of depth and magnitude, plus a set of consistent mag-area, mag-length, and slip-length relationships (where the latter is slip at a depth of ~6km rather than an average over the entire depth range). This will also require mutually consistent definitions of upper and lower seismogenic depth, aseismicity factor, and coupling coefficient (to the extent these parameters remain relevant). <i>See appendix for further discussion of this task.</i>	B. Shaw , Hanks , Somerville, Page , Beeler , Wesnousky, Seok Goo Song
	R3) Paleoseismic Recurrence Interval Estimates	Update and/or add to Tom Parsons' compilation of mean recurrence interval (MRI) estimates for paleoseismic sites. We also need to consider independence of these from slip rate estimates at the same locations. How gray can the literature be for sites in this compilation? LEADERSHIP WILL BE RESOLVED WHEN WE DECIDE ON EXACTLY WHAT WE NEED. <i>See appendix for further discussion of this.</i>	Parsons or Biasi , Weldon, Dawson, & Grant-Ludwig
	R4) Probability of Seeing Events in a Paleo Trench	We need a model giving the probability that a given magnitude event below a site would be seen in a paleoseismic trench (an update of Youngs et al., 2003).	Weldon , Petersen , Biasi, Dawson.
	R5) Solve the Large Inversion Problem	Determine whether we can solve the large inverse problem (solving for the rate of all events), including the ability to adequately sample the solutions space. Here "moment-balancing" may be replaced with slip-rate balancing at a specific depth (e.g., at a depth where overall aseismic slip is a minimum) if we can get the model mentioned above for average slip as a function of depth and magnitude. <i>See appendix for further discussion of this task.</i>	Page , Field , Parsons, Jordan
	R6) Fault-to-Fault Jumping Probabilities	Develop models of fault-to-fault jumping probabilities (relative to the likelihood of through-going rupture if there were no separation, no change in strike or faulting style, or no change in whatever metric is used to define the probabilities). What's needed here is a review of the literature (both observational and theoretical), a recommended applicable model based on this review, and a research agenda for making further progress. One issue is the fact that empirical studies were conducted after given earthquakes, as opposed to being based on the more uncertain information we have before events. Another question is how we quantify and utilize uncertainties in fault endpoints? Finally, do we develop generic rules or do we consider each possible connection in our fault model on a case-by-case basis (probably the former since we want testable rules).	Harris , Jackson, Wesnousky, Dawson, & Biasi, J. Shaw?
	R7) Reassess Historical Earthquake	Evaluate whether there may be biased estimates of magnitude and locations from felt reports. For example, treat larger events as lines rather than points. <i>See appendix for further</i>	Parsons , Bakun?

	Catalog	<i>discussion of this task.</i>	
	R8) Reevaluate Earthquake Catalog	Reevaluate association of events with different faults, and use both historical and instrumental catalogs to determine rates, including the total magnitude-frequency-distribution, using whatever approaches are appropriate (e.g. a range of declustering models, various methods of dealing with parameter tradeoffs in rate determination). One question is how much of an inferred magnitude bias would be needed to remove the discrepancy between predicted and observed rates. Can we pinpoint exactly what data or model components are influencing the discrepancies? Another question is whether we can estimate the magnitude frequency distribution for “off fault” events. <i>See appendix for further discussion of this task.</i>	Michael, Felzer , Bakun, Parsons, Schorlemmer, Hardebeck
	R9) Smoothed Seismicity Model	Reevaluate procedures for smoothing instrumental seismicity in light of both RELM test results and precarious rocks implying that spatial smoothing should be tighter. <i>See appendix for further discussion of this task.</i>	Felzer , Mueller , Biasi, and Grant-Ludwig
	R10) Mmax for off-fault seismicity	Develop more quantitative estimates of maximum magnitude for off-fault seismicity, either by considering the size of those faults left out of the deformation model (for lack of a slip rate) or by what’s needed to satisfy the extra deformation in our previously defined type-C zones (or any new zones defined by the more sophisticated deformation models discussed above). This will allow us to merge C zone sources into the background, which would be good in terms of removing an existing artificial distinction. <i>See appendix for further discussion of this task.</i>	Parsons , Field , Michael
	R11) Focal mechanisms of off-fault seismicity	Define the probability for different focal mechanisms as a function of space throughout California (for events not on modeled faults). <i>See appendix for further discussion of this task.</i>	Jackson , Hauksson
	R12) Distribution of Slips in Paleo Trench	Get an update on the Hecker/Abrahamson contention that trenches reveal characteristic slip (slips seem to be the same over multiple events)	Weldon , Hecker, Dawson, & Biasi
	R13) Evaluate Physics Based Earthquake Simulators (for rate estimates)	Investigate implications and applicability of physics based simulators for inferring the long-term rate of all possible ruptures (as well as other things). Do this in conjunction with the ongoing SCEC working group. <i>See appendix for further discussion of this task.</i>	Field , Michael, Tullis, Dieterich, Richards-Dinger, Ward, Rundle, Pollitz , Beeler
	R14) Reconsider aleatory uncert. in Mag from given Area	Currently we give a range of magnitudes for a given fault-rupture area, but this potentially gets double counted in hazard calculations because attenuation-relationship sigmas implicitly include a range of areas for a given magnitude. Perhaps we should include this when stating earthquake probabilities, but exclude it in PSHA? This is a very important issue for SCEC’s CyberShake project. We need to have a cooperative workshop CyberShakers, NGA developers, and other ground-motion modelers to address this issue.	Field , Campbell, Graves, others?
	R15 Cascadia subduction zone	Develop a complete, revised model for Cascadia. Note that this component will be developed somewhat separately from the rest of UCERF3 because it is mostly outside California and has a different set of issues and data constraints. There will be significant overlap in participation, however, ensuring that model assumptions and methods are not contradictory. <i>See appendix for further discussion of this task.</i>	Frankel , Weldon, Petersen

	Task	Description	Participants
Earthquake Probability Model(s)	P1) Address “Empirical” model	Examine robustness of apparent rate changes given reevaluation of historical catalog (task above) and for different time and space slices. <i>See appendix for further discussion of this task.</i>	Felzer , Parsons
	P2) ETAS explains Empirical Model?	Investigate whether ETAS is sufficient to explain the observed rate changes in the empirical model. <i>See appendix for further discussion of this task.</i>	Felzer , Page , Michael?
	P3) Coulomb Stress explains Empirical Model?	Investigate whether static coulomb stress changes can explain the observed rate changes. <i>See appendix for further discussion of this task.</i>	Parsons , Powers? , Pollitz
	P4) Develop self-consistent renewal models	Develop self-consistent, elastic-rebound-motivated renewal models, which are currently lacking for anything but strictly segmented models. This will likely require exploring synthetic earthquake catalogs produced by physics-based simulators. One approach that may work involves an average time-predictable model, which requires having slip in last event along the fault. <i>This issue has been described extensively in Appendix N of the UCERF2 Report.</i>	Field & Page
	P5) Implement ETAS for spatial-temporal clustering	Our first order application will be a simple ETAS model where the triggered events will be sampled from the long-term rate model (so that magnitude 8 events can only be triggered where such events can occur in the long-term model). Questions here include: 1) will we need to compute spatially variable ETAS parameters to reflect the fact that the long-term magnitude-frequency distribution is spatially variable (and perhaps non Gutenberg Richter)?; 2) should we follow the current practice of the STEP model and compute temporally variable or sequence specific parameters or is the range of variability consistent with a single set of ETAS parameters?; 3) what should the lower magnitude limit be for updating the forecast based on observed seismicity (M3?); 4) will the fraction of main shocks versus triggered events be magnitude dependent? Our strategy will be to start with the simplest model and add complexity as needed to satisfy data or other constraints. <i>See appendix for more discussion of this task.</i>	Michael , Felzer , Page , Field , Gerstenberger, Parsons, Michael , Jones, Jordan, Powers
	P6) Evaluate Agnew and Jones	Does the Agnew and Jones (1991) approach constitute a unique and implementable model? <i>See appendix for further discussion of this task.</i>	Michael
	P7) Evaluate Static Stress Change Models	Do static-stress change models constitute unique and implementable models (from an operational perspective)? <i>See discussion of Task P3 in appendix for further discussion of this task.</i>	Parsons , Powers
	P8) Evaluate other time dependencies	Are there important rate variations at other time scales (e.g., implied by empirical model, or by the mode switching identified by Rockwell and Dolan in paleo data). How do we model these? <i>See appendix for further discussion of this task.</i>	Hardebeck , Dolan?
	P9) Evaluate Physics-based simulators (for probabilities)	Investigate implications and applicability of physics based simulators for inferring elastic-rebound probabilities and clustering effects. Do this in conjunction with the ongoing SCEC working group. <i>See appendix for further discussion of this task.</i>	Field , Michael, Tullis, Dieterich, Richards-Dinger, Ward, Rundle, Pollitz, Beeler

	Task	Description	Participants
Implementation Issues	I1) Documentation and access to input data and results	UCERF2 created issues with respect to the delivery of data and model results, especially with respect to how the NSHMP provides this information. Relaxation of segmentation and allowing fault-to-fault ruptures will only compound these issues, so we need to start thinking about solutions now.	Field, Haller, Petersen, McCarthy, Wills, Dawson, Jordan, Milner, Husband
	I2) Loss Modeling Tools	Develop loss-modeling tools to help quantify what model uncertainties are important (a “tree-trimming” tool). Such tools would also allow us to quantify the practical implications of UCERF3 enhancements (e.g., spatial and temporal clustering). Note that this activity is not part of the CEA-sponsored scope of work. Funding for this activity remains in question.	Porter, Field, Luco
	I3) Address potential issues for the user community	User-community issues that will be raised by UCERF3 include 1) how they will deal with much larger event sets (due to relaxing segmentation and allowing fault-to-fault ruptures); 2) changes in the definition of “aftershocks” and how or if they’re removed from the complete UCERF3 model (this is important because building codes currently have aftershocks removed, and CEA’s earthquake insurance policies have specific and important wording with respect to the definition and treatment of aftershocks); and 3) how hazard and loss calculations can most efficiently be conducted from an operational earthquake forecast (where probabilities may be changing in real time)	Field, Luco, Petersen, Porter, Campbell
	I4) Address IT issues in deploying an operational earthquake forecast	UCERF3 will involve real-time interoperability with seismic network information in order to update probabilities immediately following significant events. A robust implementation will be very important, including how the model interfaces to user communities. What exactly are we promising, and do we have the stomach for long-term operations given this will require dedicated resources that don’t currently exist?	Powers, Field, Milner, Jordan, Gerstenberger, Jones, Earle, Petersen, Buland, Michael
	I5) Model testing	Outline a clear strategy for testing both model predictions and embedded assumptions via coordination with CSEP. The first step will be to list all the assumptions that are likely to be made in UCERF3. We will then conduct a workshop (listed below) to discuss how each might be formally tested.	Schorlemmer, Jackson, Jordan, Field, Felzer, Page, Michael, Weldon

Other Possible Tasks:

- Conduct a more comprehensive and multidisciplinary evaluation of the distribution of aseismicity. This could include consideration of: a) microseismicity hypocenter distributions; b) geodetic modeling (e.g., relationship of locking depths to seismogenic depths); c) relationship of any spatial variations in b-values to the distribution of creep (is the former a proxy for the latter?); d) kinematic inversions; e) dynamic rupture modeling;

f) physics-based earthquake simulators; and g) the relationship of proposed segment boundaries to creeping patches. Each of these is being pursued somewhat separately, so the questions is whether a more combined effort would be useful.

- Formalize rules for data inclusion to avoid some double standards that existed in developing UCERF2.
- Contribute to the compilation of a precarious-rock-constraint database, which might inform our maximum-magnitude estimates and/or procedures for smoothing background seismicity.
- Compile a list of key assumptions that are likely to be made in UCERF3 in order to facilitate discussions and for more formal testing procedures (e.g, via CSEP).

Planned Workshops & Review Meetings

The following two tables list currently anticipate SPR review meetings and workshops, respectively. Workshops, which by definition here include participants from the broader community, are aimed at addressing one or more topical issues. The review meetings, on the other hand, will involve formal evaluations by the SRP and possibly members of CEPEC, NEPEC, and the CEA science evaluation team. The topics and/or dates are subject to change as plans evolve, and it is possible that some of the review meetings and workshops will be coordinated for efficiency. Not listed here are the many anticipated meetings among WGCEP participants, as well as those that might be convened by the USGS National Seismic Hazard Mapping Program to satisfy their requirements (e.g., they are currently organizing a workshop on Cascadia that is not listed below).

Planned SRP Review Meetings

Review Meetings	Description	Date
1) Methodology Assessment	An overview of both Report #1 (Issues and Research Plan) and Report #2 (Proposed Solutions to Issues)	November, 2010 (about a month before Report #2 is due)
2) Proposed UCERF3 Plan	A comprehensive overview of the UCERF3 implementation plan (Report #3)	Mid June, 2011 (~2 weeks before SRP Report (#4) is due)
3) Preliminary UCERF3 Model	A comprehensive overview of the preliminary UCERF3 model (Report #6).	Mid April, 2012 (~2 weeks before SRP Report (#7) is due)

Planned Workshops

Title	Description	Date
Past		
UCERF3 Planning Meeting	This workshop, which had broad community participation, was to discuss the goals and anticipated issues with building UCERF3.	Feb. 17-18, 2010
Incorporating Geodetic Data into UCERF3	This workshop began a comprehensive scientific discussion of how to incorporate GPS constraints on strain rates and fault slip rates into UCERF3.	April 1-2, 2010
Future		
Statewide Fault-Model & Paleoseismic Data	This workshop will address what changes are in order for the statewide fault model, with particular emphasis on our understanding of fault endpoints and potential biases in slip-rate estimates for the lesser faults. This workshop will also address paleoseismic trench data and its interpretation.	Oct., 2010
Distribution of Slip in Large Earthquakes	This workshop will address the following: a) slip distribution along strike, especially when multiple faults are involved; b) slip distribution down dip and whether larger events penetrate deeper (important for resolving current mag-area discrepancies); and c) theoretical and observational constraints on the propensity for ruptures to jump from one fault to another.	Oct., 2010
Instrumental & Historical Seismicity	This workshop will review issues and proposed solutions with respect to the historical and instrumental earthquake catalogs, with particular emphasis on how this influences: a) the association of events to specific faults; b) inferred temporal variations in earthquake rates; and c) regional magnitude-frequency distribution estimates. This workshop will also address best practices for estimating the spatial distributions of a-values, maximum magnitudes, and focal mechanisms for background seismicity (events off our explicitly modeled faults).	Nov., 2010
Assumptions & Model Testing	This workshop will review likely UCERF3 assumptions and discuss how these might be formally tested.	Nov., 2010
Time-Dependent Models	This workshop will address what represents both “best-available science” and implementable models with respect to time-dependent probabilities in our UCERF3 operational forecast. Of particular emphasis here will be the interpretation of the empirical model, how to apply elastic rebound in unsegmented fault models, and how to represent spatial-temporal clustering.	Feb., 2011
Use of Physics-based Simulators	This workshop, which will be co-convened with the SCEC earthquake-simulators working group, will address what physics-based simulations can provide with respect to defining both long-term earthquake rates and shorter-term probabilities. As earthquake simulators hold promise for addressing many of our current goals and challenges, this workshop will be critical for gauging the maturity of these models.	Feb, 2011 (coord. w/ the above?)
Possible Implementation & User-Community Issues	This workshop among key stakeholders and general users will address anticipated issues associated with using UCERF3. Particular emphasis will be given to dealing with the significantly increased number of events, given the relaxation of segmentation and inclusion of multi-fault ruptures, as well as challenges associated with using a real-time, operational forecast.	March, 2011
UCERF3 Deformation Models	This workshop will present new deformation models based on a more sophisticated analysis and treatment of GPS data, as well as present the vision for making further progress in the future.	April, 2011
Overview of UCERF3 Plan and Preliminary Model	This workshop will constitute a complete overview of the anticipated UCERF3 model to the broader community. The timing of this workshop is to enable feedback to influence the final product.	Feb., 2012
Overview of UCERF3 for user communities	This will present UCERF3 to key stakeholders and user communities with the goal of facilitating use of the model.	Sept., 2012

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Appendix – Detailed Task Descriptions

Task F1 - Update Faults

Task Leader: Tim Dawson (CGS)

A key component of the UCERF3 study is the statewide fault model database, which specifies the spatial geometry of known active faults and provides the basis for building a fault-based earthquake rupture forecast. This task will develop a revised California fault model and focus on a re-evaluation of the faults included in the UCERF2 fault model, as well as identifying faults from recent studies that should be considered for inclusion in the UCERF3 fault model.

Background: UCERF2 relied heavily on two primary sources for defining the fault geometry used in the fault model. The Community Fault Model (CFM) developed for southern California (Plesch and others, 2007) provided much of the geometry for the major active faults in southern California, while the 2002 National Seismic Hazard Map (NSHM) fault model (Frankel and others, 2002) provided the fault model for the remainder of the State. The UCERF2 fault model also included additional revisions by WGCEP 2007 although, for the most part, the revisions to the fault geometries of the CFM and NSHM were minor. Recent studies either published or in progress, are leading to a better understanding of fault locations, geometries, and rates of deformation throughout California. Integrating these new data into the UCERF3 fault model will be the primary objective of this Task, and lead to an improved representation of the known active faults included in the fault model.

The task will include:

- *Integration of new faults and revision of existing faults from recent studies.* Recent studies defining the location, geometry, and deformation rates of faults in California are available for inclusion in the UCERF3 fault model. For example, the new Fault Activity Map of California (Jennings and Bryant, 2010) represents the most up to date compilation of active fault traces in California and includes newly mapped faults not included in the UCERF2 fault model. Defining the three dimensional geometry of these faults will be a component of this task. Ongoing work by the USGS and PG&E, synthesizing geology, geodesy, and geophysical studies, is leading to an improved understanding of faulting and the tectonics of the Central Coast Ranges. This work is being used to develop a fault model for the central coast for use in geodetic block modeling and an updated PSHA for the Diablo Canyon Nuclear Power Plant. Coordination with this work and its integration into the UCERF3 fault model will lead to a better representation of active faults within the Central Coast Ranges. New mapping of other faults, such as the Maacama fault (Sowers and others 2009) and Bartlett Springs fault (Lienkaemper and Brown, 2009) is leading to a better understanding of these faults at the surface, and an evaluation of this mapping will provide valuable insight in how these faults will be defined in the model. The full scope of work is not limited to the aforementioned faults, and a search of the

available literature will be conducted for the entire State as part of this effort. As in UCERF2, alternative viable fault models, where appropriate, will be included in order to capture the epistemic uncertainties associated with the possible fault geometries.

- *Integration of the Statewide Community Fault Model into the UCERF3 fault model.* An ongoing SCEC-funded effort is being led by John Shaw and Andreas Plesch (Harvard) to develop a Statewide Community Fault Model for California (SCFM). SCFM will likely be a major improvement to the fault geometries used in UCERF2, particularly for northern California where many of the fault geometries are legacy geometries from previous versions of the National Seismic Hazard Maps and have not been reevaluated systematically. Another potential contribution of SCFM to UCERF3 is a revised seismogenic depth surface, based on the Waldhauser and Schaff (2008) relocated catalog. This depth surface is used to define the lower boundary of the fault surfaces in the model and may lead to better estimates of the base of seismicity for many of the faults in the model. The integration of the SCFM faults into the UCERF3 will lead to a more complete active fault catalog and better representation of fault geometries in the model. Part of this effort will include a comparison between the SCFM and UCERF2 models in order to identify areas with significant changes in the fault model representations. The documentation of these changes will be important if there are large changes in the earthquake rupture forecast in different regions of the State and these changes need to be explained. We expect that some UCERF3 efforts, such as an evaluation of fault endpoints and fault junctions, will benefit SCFM as well. Because UCERF3 will be reexamining fault endpoints for a number of faults in California, new information developed from this effort can be incorporated into SCFM to improve the Statewide model. A draft version of SCFM is scheduled for released in Fall 2010. Coordination the UCERF3 and SCFM efforts will be essential in order to ensure consistency between the models and this cooperation is already underway.
- *UCERF3 fault model as a foundation for GPS block models.* A significant amount of UCERF3 resources are being dedicated to the evaluation of geodesy-based deformation models. In the UCERF2 fault model, many active faults with poorly constrained or unknown slip rates were not included in the hazard calculation. A major question that UCERF3 will address is whether GPS-based deformation models can provide slip rates on faults where there are no geologic slip rate estimates. One approach is the use of block models in order to constrain fault slip rates using geodesy. A full catalog of active and potentially active faults will need to be developed in order to provide the GPS block modelers a consistent set of faults and fault geometries from which they can build their block models. We expect this interface between the geologically defined faults and the geodetic modelers will be ongoing throughout the course of this project. For example, strain rate maps being developed by the geodetic community may highlight areas where a closer examination of the geology is warranted to look for features indicative of active tectonics and assess the current state of geologic understanding of these areas. This may

result in the addition of faults to the model that are defined as active based on geodetic evidence.

Deliverables: An updated fault model that includes the most up to date fault locations and geometries for California. The fault model will include documentation describing significant changes from the UCERF2 model as well as the rationale for these changes. This fault model (Version 3.X) will provide the basis for the UCERF3 fault-based earthquake rupture forecast as well as provide the basis for the block models used in geodetic modeling.

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Task F2 – Reevaluate Fault Endpoints

Task Leader: Tim Dawson (CGS)

One of the issues UCERF3 will address is how to relax segmentation and accommodate fault to fault ruptures within the UCERF3 model framework. A detailed inventory of fault traces, as well as three-dimensional representations are available for faults within the UCERF study region through compilations such as the Fault Activity Map of California (Jennings and Bryant, 2010) and the Community Fault Model for Southern California (Plesch and others, 2007). However, not explicitly included in these compilations, is a characterization of fault endpoints. Do the faults simply end on a map, or are there associated structures, such as connecting faults or folding, that accommodate deformation between one active fault to the next? Does an active mapped fault trace end because that is where the fault physically terminates, or is there a lack of suitable geology that records evidence of active faulting further along strike? What are the

uncertainties associated with each endpoint? What can geology, geophysical data, and seismicity tell us about how faults end and accommodate deformation from one fault to another?

The goal of this task is a systematic reevaluation of fault endpoints for the faults in the UCERF3 fault model with a focus on looking at fault pairs that may participate in multi-fault ruptures. This characterization will synthesize available geologic, geophysical, and seismicity data in order to characterize fault endpoints and search for possible connecting structures between faults. Such structures may be expressed as surface faults or folds between major faults, boundaries defined by gravity or magnetic anomalies, or alignments of seismicity. Available geologic mapping will provide information regarding the surface expression of deformation between fault pairs. Additional data, such as subsurface information from geophysical profiles, and double-difference relocated seismicity can provide additional information regarding the three-dimensional geometry of fault pairs and how they connect at depth.

A separate, but related issue, are the uncertainties in the location of fault endpoints. It is important to keep in mind that much of the original fault mapping in these compilations was not done with the perspective of multi-fault ruptures. Also, the surface manifestation of structures between faults can be subdued, or not preserved in the geologic record because areas between faults are often either extensional or compressive regimes, where geologic evidence of faulting is obscured by burial or erosion. Is there sufficient existing geologic information to adequately characterize these areas, or are there substantial gaps in our understanding of these areas that we need to consider them as highly uncertain? Figure 1 illustrates an example of this issue where no active faults are currently mapped between the Mohawk Valley and Polaris fault systems in Northern California. However, as shown on the map, there are bedrock faults that could provide a direct connection between these two faults. What is unknown is whether or not these faults are truly “inactive”, or if evidence of recent activity is obscured by surface processes, such as recent glaciation. Another possibility is that the available geologic mapping in this area is not adequate to say one way or the other. Assigning uncertainties to the fault endpoints may have important implications on what fault pairs are allowed to rupture together. In the example above, if the mapping was determined to be unresolved between these two faults, then the uncertainties assigned to the terminations of the two faults would be rather large, perhaps enough to allow a direct connection between them. If, on the other hand, the geologic evidence was sufficient to say that the gap in active faulting is real, then the uncertainties associated with each fault endpoint would be small, and an earthquake spanning the ~10 km gap between these two faults would be considered highly unlikely.

Another example of a fault system that will need to be reevaluated in the context of multi-fault ruptures is the Great Valley System (Sections 7 – 14) that bounds the west side of the San Joaquin Valley. As currently represented in the UCERF fault model, this fault system is nearly continuous and a candidate for allowing fault to fault jumps. However, these representations are adopted from the 2002 National Seismic Hazard Map (NSHM), which did not consider multi-fault ruptures in the model. Simply adopting the NSHM model may not be an appropriate approach if these “legacy” faults are generalized seismic sources and the endpoints, as well as subsurface geometries, are not well characterized.

An additional element of this task is to revisit the “Connect more B-faults option” that UCERF2 included in an attempt to model larger faults from sets of shorter faults. The faults were connected because their orientation, proximity, structural style, and slip rate are similar enough

that they are believed capable of rupturing together. However, this process was largely *ad hoc* and the specific reasons why faults were connected are not well documented. This task will develop a database for each potentially connected fault pair, describing features such as proximity (both surface and downdip), faulting styles, kinematic compatibility, and slip rate, as well as describe the rationale for connecting faults. This database will be necessary if UCERF3 adopts a “rules based approach” for Task R6 (Fault to Fault Jumping Probabilities), where a set of predetermined rules, specifying to criteria necessary for faults to rupture together, will be applied to faults in the model. If fault to fault jumps are considered on a case by case basis, this database will still be useful in helping to identify fault pairs capable of rupturing together.

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Figure 1. Area between the active traces of the Mohawk Valley and Polaris fault systems showing bedrock faults as possible connection. (Jennings and others, 2010).

Task D2 – B-Fault Bias

Task Leader: Ray Weldon (UO)

Statement of the Problem: There is some evidence that poorly studied, generally low slip rate faults have rates that are systematically overestimated. This is due to several factors including the fact that once one recognizes that a fault is active, its minimum slip rate is always greater than zero, so if its upper limit is poorly defined, its total slip rate range is centered at a rate greater than the actual rate. For example, if a fault with a slip rate of 0.1 mm/yr is recognized as active, but its upper rate can only be limited to less than 1 mm/yr, its range is reported as 0-1 mm/yr, which is then modeled as 0.5 ± 0.5 mm/yr. Other problems include the fact that one often can only determine rates of low slip rate faults at places where their rate is greater than average, and thus most easily studied biasing the rate if it is used as an average, and finally, when presented with equivocal data geologists appear to unconsciously prefer larger offsets and higher slip rates, simply because it makes their results more exciting and relevant.

Proposed Solution: 1) We propose to review the evidence that goes into determining the slip rate of all B faults, as part of our larger effort to review the slip rates of all of the faults in our model, with an eye to detect and eliminate the upper bias. 2) We intend to explore probability distribution functions to better capture the asymmetrical distribution of error. 3) We intend to look at the cumulative strain (using line integrals and strain tensor analysis) in regions with large numbers of B faults to see if we cap the total slip rate for groups of faults and thus better define the upper limits of individual faults that contribute to the total.

Task D3 – Line Integral Tools

Task Leader: Tom Parsons (USGS)

This task is intended to offer testing opportunities for the fault and deformation models, and is intended to supplement strain tensor and slip budget analyses conducted under UCERF2. Progress to date on new tools includes completed programming that converts UCERF fault and deformation model database formats into 3D elastic dislocations (Fig D6f1) that can be slipped according to their estimated slip rates and rakes. Thus the implications on long-term deformation can be examined and compared with observables such as overall plate boundary displacement rates. Further, line integrals drawn along random paths through the model that sum displacement should close.

One significant advancement proposed is to assemble uplift and subsidence rate observations where possible. This is because the deformation model is assembled with the plate boundary rates in mind; thus the extent that they match is not necessarily an independent test. However, predicted patterns of uplift and subsidence from the fault and deformation model (Fig. D6f2) are more independent from considerations related to the input during model development. Significant mismatches between observed uplift and subsidence, or recent topography could indicate problems with the fault and/or

deformation models, and potentially help with distinguishing between, or weighting of competing models.

Another potential use of the dislocation model tools is in mapping stress concentrations that result from slipping the faults. If very large stress concentrations result from slipping the model faults, this would be an indication that the deformation model may be incomplete in terms of absorbing plate boundary stress.

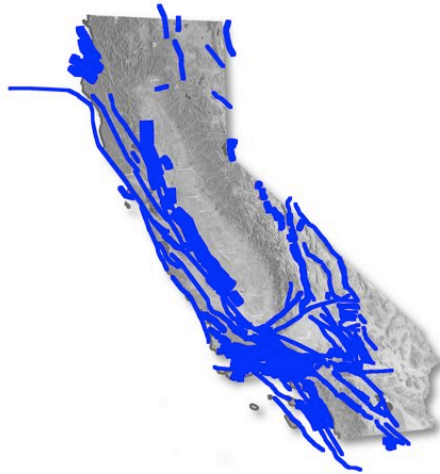


Figure 1. 3D dislocation model of California faults as of UCERF2.

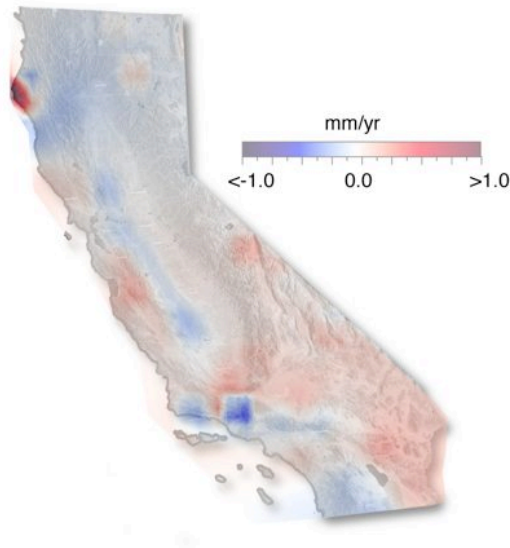


Figure 2. Calculated uplift and subsidence resulting from slipping faults in the UCERF2 deformation model.

Task R1 - Evaluate Along-Strike Distribution of Average Slip

Task Leader: Glenn Biasi (UNR)

In UCERF-2 rupture displacement along strike for faults was modeled using a rupture profile developed by averaging over multiple events (Biasi and Weldon, 2006; Biasi and Weldon, 2008). To average over multiple ruptures, ruptures were first normalized by length and by average displacement. The resulting average shape compares extremely well with a functional form, $\sin(x/2L)^{1/2}$. This shape fits well across a range of subsets also, including only short (<30 km) ruptures and only events >200 km in length. The average shape is something of a statistical construct, and not expected for any particular earthquake.

We plan to assess more systematically the assumptions and consequences of assumptions behind this simple, empirically observed shape. First, normalizing by rupture length assumes that the spatial variability of displacement of short ruptures is similar to that of long ones. Second, by normalizing by displacement, real differences among ruptures can be removed. Using this shape can, in effect, create ruptures reflecting a constant stress drop (Shaw, 2009). Mechanically this may make sense, but either way, the consequences of normalizing by average displacement should be clearly understood. Available data may be sufficient to evaluate both of these assumptions.

When multiple fault segments are involved, it is not known whether the sub-fault sections follow this general shape. Also, rupture step-overs are characterized by greater degrees of distributed displacement, rotation and extension at the ends, and distortion of displacement gradients. We plan geologic and geometric assessments of step-overs, which should give clues to the mechanical linkage of fault sections. We have identified 12 events in the data of Wesnousky (2008) likely to be of immediate use. Understanding the Landers earthquake will be important for UCERF-3 efforts to link B-faults because multiple faults were involved, and because the rupture did not follow the full lengths of the available B faults that it did use.

We also find that the average displacements of sub-fault ruptures of the Landers event are almost all too large to be predicted using standard scaling from their lengths. This suggests that the sub-faults were not individually loaded and accidentally ruptured together, but rather that they are resolving strain buildup of a larger, integrated system. We will investigate whether this a general feature when Type B or C faults link. How do short faults “know” what displacement to have? If displacements on short faults reflect the final event magnitude, and not some more natural size scaled by their length, what is the mechanism? Can it be identified and used in a predictive understanding of fault linkages?

We will be using the data and descriptions of Wesnousky (2008) as a primary resource. To update this list we have identified the following earthquakes as either postdating his compilation, or that were not included for other reasons but that might be useful in the present work:

2010 Sierra El Mayor, Mexico
2009 L’Alquila, Italy

2008 Wenchuan, China
 2006 Machaze, Mozambique
 2005 Pakistan
 2004 Parkfield, California
 2004 Mid-Niigata, Japan
 1995 Kobe, Japan
 1976 Montagua, Guatemala
 1973 Luhuo, China
 1931 Funyun, China
 1905 Bulnay, Mongolia

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Task R2 – Evaluate Magnitude-Scaling Relationships and Depth of Rupture

Task Leader: Bruce Shaw (LDEO)

The standard seismic hazard approach of using magnitude-area scaling laws to construct earthquake rupture forecasts has run into inconsistencies when combined with physics-based methods of simulated ground motion, in that ground motion estimates end up being too high. The ultimate goal of this work is to satisfy large-earthquake scaling observations in ways which can be used to balance slip budgets for use in earthquake rupture forecasts, while also being consistent with downstream ground motion estimates. As a first stage, developing two alternative pathways for size-length scaling and slip budget balancing are proposed. One pathway will be based on the more traditional magnitude-area scaling relations. The work on this pathway will

review existing scaling relations, and examine ways they might be modified to be more consistent with ground motion estimates. One generalization we will explore will allow for the possibility that some of the co-seismic moment may be happening deeper than the seismogenic depth. Accounting for long period motion contributing to moment, and short period motions contributing to shaking would be part of this project, along with ways to project the long period moment onto seismogenic depths for slip budgeting. Regarding the possibility of large ruptures propagating coseismically below the seismogenic layer, examining the role of different constitutive equations at depth, in particular a central rate-and-state feature of logarithmic velocity strengthening will be included in this effort. Reviewing alternative models for use in earthquake rupture forecasts will be an outcome of this work.

A second pathway for slip budgeting, as a means for trying to span alternative models and trying to build on directly observable variables will also be developed. Here, we propose to develop scaling and budgeting around surface slip observations. These scaling laws have the advantage of being directly geologically observable. Combining average slip as a function of length, with moment as a function of length, gives an alternative pathway for slip balancing on faults. To expand the class of viable models, we propose to develop this second pathway for use in the earthquake rupture forecasts. Having developed these potential scenarios, integrating them with ground motion modeling would be a clear next stage. This aspect would be best done in collaborative mode, which we propose to initiate this year, anticipating results and feedback from this collaboration in following years.

To summarize in terms of deliverables, we thus propose three specific elements. One element will be a peer-review-ready document reviewing magnitude-area scaling laws and slip budgeting and their use in earthquake rupture forecasts. Some of these scaling laws will include the possibility of ruptures extending coseismically below the seismogenic layer. A second element will be a peer-review-ready document discussing the second slip-length pathway. A third element will be an effort to develop a collaboration with ground-motion modelers. This collaboration would seek to integrate the scaling laws with ground motion estimates to find ways to develop relations consistent with both size-length scaling observations and ground motion observations.

Task R3 - Paleoseismic Recurrence Interval Estimates

This task is aimed at developing interevent times at points where paleoseismic data are observed. There are a number of approaches to this problem that depend on the intended use of the parameters. The UCERF2 exercise calculated earthquake rates according to fault slip rates. These values were then checked for consistency with paleoseismic event rates. Two methods were used, in southern California, the stringing-pearls methods of Biasi et al. [2002] and Biasi and Weldon [2009] were applied along the San Andreas fault. For the rest of California, a Monte Carlo approach [Parsons, 2008a] was used to test observed intervals against different recurrence models.

The paleoseismic database contains lists of intervals within which events of unspecified size caused surface ruptures. An initial step under this task will be to reassess the database of

paleoseismic information, and potentially add new observations. Uniform, consistent criteria for adding or omitting data based on quality and/or publication status will be developed.

Three uses of these observations are envisioned: (1) simple event rates can be calculated using a Monte Carlo approach just to account for open interval uncertainty [Console et al., 2008] with no underlying recurrence PDF assumption. These numbers could be used to constrain inversions for long-term surface-rupturing earthquake rates at points, and give just raw number of events over some duration. (2) Earthquake rupture histories can be found by linking multiple observations along the same fault strand. This process adds a magnitude constraint on segments, which can limit the solution space for inversions because they would then be required to produce rates of different magnitude events that match the earthquake history (and its uncertainties). (3) Direct probability calculations can be made at points based on paleoseismic information: output from traditional segmented characteristic rupture models, or from rate inversions are assumed to obey some recurrence PDF (Brownian Passage Time (BPT) and exponential were used in UCERF2), which leads to probability calculations of future occurrence. In some cases where there are quality paleoseismic data, the same assumptions can be made about recurrence PDF's, and observed intervals can be developed into rate models that are independent of slip-rate based earthquake rate calculations. Because these values are calculated assuming an underlying recurrence model, they can have narrower uncertainty ranges than those caused by fault geometry, slip-rate, and segment boundary definitions (Figure R31). The most appropriate time to make this comparison is at the probability-calculation step.

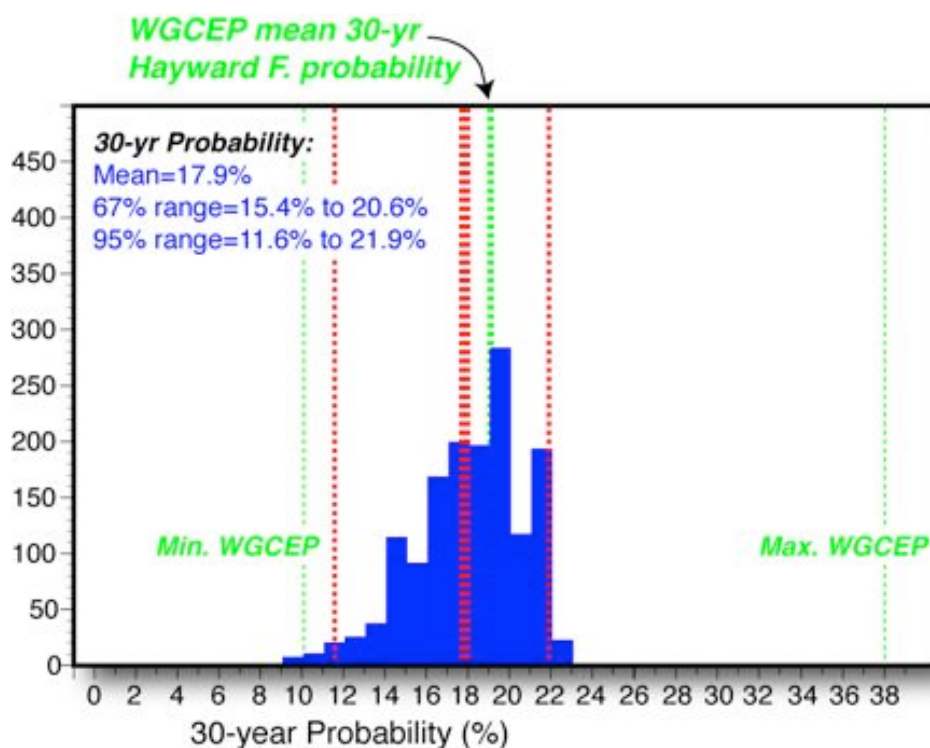


Figure 1: Comparison of Hayward fault probability calculated by UCERF2, and by direct use of intervals from paleoseismic observations. The range of possible probabilities is narrower in the paleoseismic example.

Lastly, the paleoseismic database can be used to test recurrence MRI's against one another for consistency. Some models will fit better than others, and the difference can be quantified. For example, Parsons [2008b] found a much better fit using BPT models than exponential for the Hayward fault series (Figure R32). Weighted solutions for aperiodicity and recurrence model PDF choices can be assessed at each paleosite, and extended to rupture processes using earthquake rate model solutions if desired.

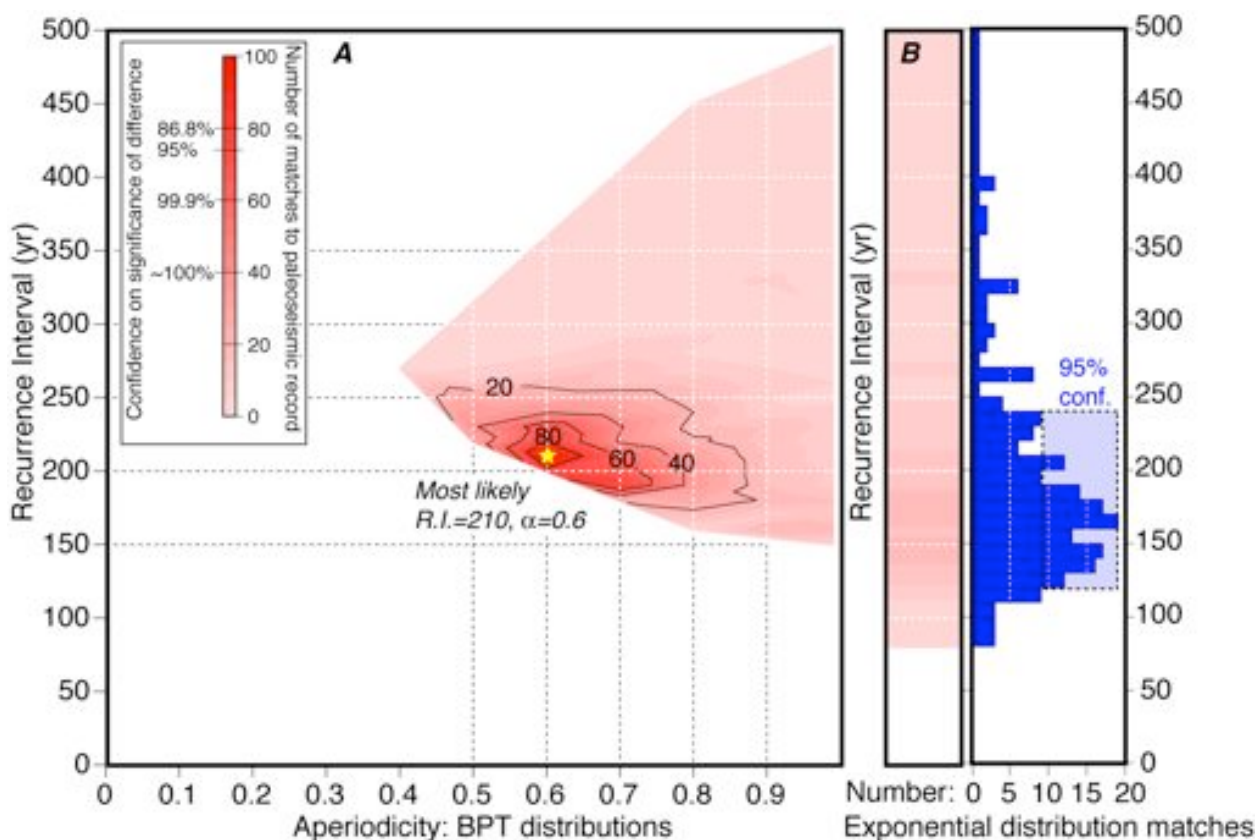


Figure 2: Contours of matches to south Hayward fault paleoseismic event series of different (a) time dependent (Brownian Passage Time) and (b) time independent (exponential) recurrence distributions. The best-fit distributions are time dependent, with recurrence intervals of $m \sim 210$ yr, and coefficient of variation $a \sim 0.6$. Confidence (Z-test) on the significance of relative proportions is keyed to the contour intervals. The best-fit exponential distributions have significantly fewer matches, leading to the conclusion that earthquake recurrence on the south Hayward fault is time dependent, possibly from a stress renewal process. A histogram of exponential distribution matches is shown in (b), with 95% confidence of significance shaded, which gives the same information as the adjacent contour mapping, but in more detail.

References:

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Task R4: Probability of Seeing Events in a Paleo Trench

Task Leader: Ray Weldon (UO)

Statement of the Problem: Paleoseismic records are incomplete because many earthquakes do not reach the surface and some of those that do reach the surface are not be recorded. To accommodate this problem many studies (including UCERF2) use the probability that a rupture reaches the surface, based on observation of historical ruptures, as the probability that an event will be observed in a trench. Because ruptures with small displacements are more difficult to preserve and be interpreted in the geologic record and because there are hiatuses in trench records, the probability that an event will be recognized in a trench must be lower than the probability that the event reaches the surface.

Proposed Solution: We propose to look at a representative suite of trench studies in different types of geologic materials to better understand what factors affect the resolution of paleoevents and thus develop general rules to estimate the completeness of the record for different sized events. Three approaches are likely to provide useful results: 1) Apply uniform semi-quantitative measures of event quality (eg Scharer et al. BSSA, 2009) to all trench sites to compare event quality between different types of sites, 2) Make summaries of the amount of offset recognized in trench studies to get a better idea of what the lower threshold of recognition of offset is in different geologic settings. For example, if the smallest offsets mapped in alluvial deposits is 10 cm, that is likely the lower resolution and surface ruptures that are likely to be less than 10 cms are not likely to be found. 3) Apply methods developed to access the completeness of stratigraphic records to trenches to assess the completeness of our trench records and to identify significant hiatuses in the records. For example, at the Frazier Mtn site on the SAF there are on average 1 distinguishable clastic unit per decade, but some portions of the section preserve only a few layers per century and other portions many units per decade. By focusing on the

resolution through time we can assess what parts of the past are well sampled and what portions are not, and thus infer when our records are likely to be complete or incomplete, and when we are likely or unlikely to recognize events that are seen in neighboring sites.

Task R5: Solve the Large Inversion Problem

Task Leader: Morgan Page (USGS)

The purpose of this task is no less than to solve for the long-term rate of all possible (“on-fault”) ruptures. Building on the work of Andrews and Scherer (2000), we can solve for the rates of ruptures that are consistent with a) slip-rate constraints, b) paleoseismic event rates, c) *a-priori* rupture rate estimates, d) smoothness constraints, and e) constraints on the magnitude distribution (Field and Page, *submitted to BSSA*). These constraints are linear and can be described via a matrix equation of the form $Ax=d$. Our task is to set up this matrix equation and solve for x , given A and d .

We will solve the inverse problem via a simulated annealing algorithm. There are several advantages of this algorithm in contrast to other approaches such as the nonnegative least-squares algorithm. First, the simulated annealing algorithm scales well as the problem size increases. Next, quite importantly, the simulated annealing algorithm gives multiple solutions (at varying levels of misfit depending on the annealing schedule). Thus both the resolution error (the range of models that satisfy one iteration of the data) and the data error (the impact of parameter uncertainty on the model) can be sampled.

Defining all possible ruptures

The first stage of this task is to define all possible ruptures based on the fault-system database. This task depends heavily on task R6 (fault-to-fault jumping probabilities) and requires generating simple rules to determine whether two faults can rupture together in a single earthquake. These rules will depend on the distance between the faults and the (incremental and cumulative) angles between segments.

A related subtask is implementing the jumping probabilities themselves. A simple binary approach would be to allow fault sections that meet the criteria (say, within the 3- to 4-km distance suggested by Wesnousky (2006)) to rupture together without penalty. Different criteria could be sampled as a component of model error. A more advanced implementation would allow, but penalize ruptures that, for example, had a large but plausible distance between different fault segments. This could be accomplished via minimization constraints in the inversion (with weights proportional to the rupture-jump probability) or by incorporating “connector faults” with low slip rates at fault junctions. Slip rates at the connector faults could be set equal to the jumping probability multiplied by the average slip rate of the database segments at the fault junction being considered.

Refinements to Inversion Setup

We will also refine the inverse problem to more appropriately include the data and its errors. One example of this involves the slip rate constraint: Currently the fault slip rates are constrained

by “data” at every section along the fault; however, many of these values are simply extrapolated from surrounding portions of the fault and do not represent independent data. An improved version of this constraint will constrain the slip rates only at points where it is independently measured; in the absence of secondary faults the slip rate between these data points can be smoothed.

Another planned refinement involved the incorporation of full probability-distribution functions for data such as the event rate constraints. Since we are using a simulated annealing algorithm, the error model for data parameters is not constrained to be Gaussian. Multiple nodes solving the inverse problem could sample the full probability distributions of the input data.

One last improvement that could be made is to replace moment-balancing with slip-rate balancing at a sufficiently coupled seismogenic depth. This relates to task R2 (Evaluate Magnitude-Scaling Relationships and Depth of Rupture Models) and could fix inconsistencies in the use of magnitude-area relationships and the assumed depth extent of rupture.

Memory constraints

In the absence of regularization, the size of the A matrix in the inverse problem scales as the number of subsections multiplied by the number of ruptures. We estimate that the large inversion problem will have approximately 200 subsections and 220,000 ruptures, which with double-precision (16-bit) elements is a 700 MB matrix. This is a feasible matrix size for modern computers that typically have 4-8 GB of memory.

Adding a regularization constraint that smooths the number of ruptures would cause the size of A to scale as the square of the number of ruptures. For our estimated number of ruptures this would give a matrix A of approximately 770 GB. This could not be loaded into memory at once. It is possible, however, to do the forward problem (multiplication of A with the model vector), which the simulated annealing algorithm requires, without loading the entire matrix A into memory at one time.

Computational time

As the problem size increases, each iteration of the simulated annealing algorithm takes longer to run; this increase scales with the time required to do the forward problem (matrix multiplication). In addition the number of simulated annealing iterations required to reach a given level of misfit increases. Based on initial tests, it appears that the computational time to reach a given level of misfit scales as $N^{1.5}$, where N is the number of matrix elements. Extrapolating this relationship from smaller problems, we estimate that the large inverse problem could be solved via a simulated annealing algorithm in approximately 16 hours. Improved agreement with data could be achieved with longer annealing times.

The simulated annealing algorithm is easily parallelizable to multiple processors. One such algorithm that could be used in a parallel algorithm of the simulated annealing component is parallel tempering, which searches multiple portions of the parameter space at the same time. Alternatively, multiple processors could be used to run the inversion on different iterations of data; this would allow the data resolution to be thoroughly explored.

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Task R6 - Fault-to-Fault Jumping Probabilities

Task Leader: Ruth Harris (USGS)

One of the primary goals for UCERF3 is to include fault-to-fault ruptures, which will require having some kind of estimate of the likelihood of such events. Ideally we would have some model giving the probability of fault jumping given some information:

$$\text{Prob}(\text{jump} \mid \text{information})$$

where that information might be one or more of the following: distance between faults, relative orientation or change in strike, style of faulting, hypocenter, overall size of the event, slip rate, etc. Unfortunately no such model exists, and it's not clear exactly how to develop one.

Another and-member approach would be to rely on expert opinion on a case-by-case basis (evaluating each possible fault combination separately). At the very least we would want this to provide a Boolean answer (yes vs no) to the question of whether a given rupture jump is possible (or better yet, a probability). This is less desirable than using an objective formula due to reproducibility and testability issues.

A third option would be to compute a “self-consistency metric” based on coulomb stress change calculations (the stress changes caused on the surface itself by the occurrence of the event). Ruptures that are red over then entire surface would presumably imply a greater mechanical compatibility (and therefore likelihood) than those that are half red and half blue (a mix of stress increases and stress drops). One question is how to normalize these calculations to give the relative likelihood for all the various ruptures.

We plan to pursue all of these approaches in developing UCERF3.

Specifically, we will convene a meeting of experts on this topic to go through the actual fault-jumping candidate pairs in California on a case-by-case basis, with the goal of defining an expert opinion probability or Boolean for each pair (we may need to prioritize according to important faults if time is an issue). By taking notes on each scenario addressed, we would hopefully build a body of reasoning that could then be used for establishing more generic rules, or even a formula as articulated above. Perhaps we could also have the coulomb calculations up and running for additional consideration at the meeting. One question is how to handle uncertainties in the faults themselves; perhaps we assume perfect accuracy for this exercise?

We may need to build on Wesnousky's fault rupture database to add new events and or new parameters that might be used for predictive purposes (fault orientation etc.). We also need to consider the fact that Wesnousky's database represents measurements taken after large events rather than from the more limited information available before an event (the latter is what we will be dealing with).

Participants of this workshop could include: Ruth Harris, Steve Wesnousky, David Oglesby, David Jackson, Ray Weldon, Tom Parsons, Peter Powers, Morgan Page, Bruce Shaw, Tim Dawson, and John Shaw (the latter two in order to inform the needs for future fault models).

The hope would be for this workshop to lead to a report defining a proposed usable model, a review of the literature, and a path forward in terms of future research.

A broader community workshop could then be conducted to review the proposed solution.

Finally, it should be noted that physics-based earthquake simulators, and/or 3D spontaneous (dynamic) rupture simulations based on probabilistic initial conditions, are other ways of addressing this problem that we will be looking into.

Task R7 - Reassess Historical Earthquake Catalog

Task Leader: Tom Parsons (USGS)

This task is intended to reduce uncertainty involving fault assignments in the historic, intensity-based earthquake catalog. Current practice uses contours of likely intensity centers to identify approximate allowable earthquake centroids. These are then assigned to likely faults [e.g., Bakun and Wentworth, 1997]. There can be a degree of ambiguity related to the point process location of large earthquakes because large rupture areas are reduced to a point.

The proposal is to modify the Bakun code to invert for solutions using the 3D California fault model. Rupture patches can be systematically added within the 3D fault model, with synthetic intensity values superposed using an attenuation relation. As more patches are added, the magnitude of the rupture grows, and larger intensities are produced from a larger region. Some limited set of fault areas will be most consistent with the observed spatial pattern of intensities. More realistic intensity patterns would be produced instead of the currently used circular intensity patterns. The resulting output would then be best-fit magnitude and fault-area assignments that lack potential interpretation bias that is necessary in current practice.

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Task R8 - Reevaluate Earthquake Catalog

Task Leader: Andy Michael (USGS)

The historic and instrumental earthquake catalog is one UCERF3's primary constraints on earthquake rates and therefore probabilities and is thus worthy of reevaluation even after the extensive work done during the UCERF2 process (Felzer, 2008a, b; Felzer and Cao, 2008). The general process is to produce earthquake catalogs and then calculate earthquake rates as a function of magnitude by either declustering the catalog to remove foreshocks and aftershocks or by fitting a distribution that includes clustering to the complete data set. A number of topics will be considered that result in epistemic uncertainty in the earthquake rates:

- 1) Different approaches to evaluating historical records to obtain intensity values. Due to the extraordinary effort required to revisit the historical records, we will evaluate the sensitivity of the earthquake rates to possible systematic uncertainties in the intensities and the resulting historic catalogs.
- 2) Different historic earthquake catalogs.
- 3) Different declustering techniques.
- 4) The effect of parameter tradeoffs when fitting models, which include clustering, on the complete (undeclustered data set).
- 5) Different methods for determining the magnitude of completeness.
- 6) Different methods of associating earthquakes with faults and/or background zones.

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Task R9: Smoothed Seismicity Model

Task Leader: Karen Felzer (USGS)

Current Status

The background seismicity hazard in Working Group models and the National Seismic Hazard Map has traditionally been assigned by smoothing declustered instrumental ($M \geq 4$) earthquake catalog data with a Gaussian function. A test by *Felzer (2009)* found that the smoothed maps agreed well with the last 30 years of seismicity; that is, the degree of localization of the declustered catalog was fairly well preserved by the smoothing kernel.

In the RELM tests the smoothed seismicity model of *Helmstetter et al. (2007)* (with updates and corrections by *Werner et al. (2010)*) which uses a narrower smoothing kernel, has been outperforming other models to date, including the 2002 National Hazard Map. This may be due more to differences in forecasts over the major faults rather than to differences in the smoothing of catalog seismicity; nonetheless some modification of the smoothing to bring it closer to the Helmstetter model seems prudent. In addition, at least parts of the background seismicity model are inconsistent with precarious rock data (*Brune et al., 2010*). Using a narrower smoothing kernel might help to correct this discrepancy.

One difference in the *Helmstetter et al. (2007)* model is the use of the catalog seismicity down to $M 2$ rather than $M 4$; *Werner et al. (2009)* found, however, that using thresholds between $M 2$ and $M 4$ did not strongly influence results, while using thresholds $> M 4$ did rapidly decrease the probability gain. Since the California catalog is incomplete below $M 4$, we therefore recommend that the $M 4$ threshold be maintained. *Helmstetter et al. (2007)* also used the *Reasenbergs (1985)* rather than the *Gardner and Knopoff (1974)* declustering algorithm, but did not test whether this change significantly impacted their results. Declustering remains a difficult issue that we discuss further below. Finally, *Helmstetter et al. (2007)* found no significant difference between a Gaussian and power law smoothing kernel, but did introduce a new method for determining the best smoothing parameters. We suggest adopting this method.

Werner et al. (2010) also found that the Poissonian did not accurately predict the number of earthquakes occurring over a given time period and suggested a negative binomial distribution.

For short term forecasting *Helmstetter et al. (2007)* used an ETAS aftershock simulation algorithm.

Research Plan

Declustering the catalog is a consistent bugaboo in producing background seismicity maps, as it involves some number of arbitrary decisions and a non-quantifiable degree of error. In addition complete declustering is not really desired, as we expect large aftershock sequences to continue to produce aftershocks for tens to hundreds of years. Instead of declustering we propose to use the modified Omori law to calculate the projected rate at which each earthquake in the catalog should produce aftershocks over the forecast period. Each earthquake in the full catalog could be smoothed with a power law or Gaussian function, and then the rate associated with that earthquake calculated in accordance with the modified Omori law and the earthquake's magnitude. This method will be most accurate if large earthquakes in the catalog are represented

as plane sources rather than as points, and if earthquakes from the historic period are included. It may also be best to use sequence-specific Omori law parameters for the larger sequences. How well this approach performs in comparison with simply smoothing a declustered catalog could be calculated via retrospective forecasts using the *Werner et al.* (2010) approach.

Because not all aftershock-producing earthquakes are in the catalog, however, (many are too small or too distant) and because there may be non-triggered seismicity, simply projecting Omori's law from catalog earthquakes is unlikely to produce a high enough total. We propose that the difference could be made up by simply increasing all of the rates, by adding in rates projected from a long term deformation model like SHIFT (*Bird and Liu*, 2007), or by some combination of the two, with the optimal recipe determined via the retrospective probability gain tests of *Werner et al.* (2010).

Finally we propose that completed smoothed seismicity map be tested against precarious rock data and that the smoothing kernel and that the relative weight of different inputs to the map (e.g. modern catalog data vs. deformation models) be adjusted until the map is consistent with the precarious rocks. We also propose to evaluate whether the apparent focusing of hypocenters on faults provided by double-difference methods (e.g., *Hauksson and Shearer*, 2005) should affect how seismicity is smoothed for ground-motion prediction purposes

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Task R10 – Mmax for off-fault seismicity

Task Leader: Tom Parsons (USGS)

This task will tackle maximum magnitude of background (off-fault) seismicity. UCERF2 used a fixed (and somewhat arbitrary?) maximum magnitude. The challenge of this exercise is to attempt to develop an informed, spatially variable Mmax assignment in parts of the state where there are no mapped faults providing any guidance. A possible approach to this is envisioned by making two assumptions: (1) Large (and large-ish) regions obey a Gutenberg-Richter magnitude-frequency distribution, and (2) that the San Andreas and other A-faults will host the overall statewide maximum magnitude events, filling in the high end of the magnitude-frequency distribution.

For UCERF3, at least two and possibly three fault-based earthquake rate models will be developed using characteristic, Gutenberg-Richter, and possibly hybrid magnitude distributions. These models will then fill in most of the histogram “bins” of the regional power-law magnitude-frequency distribution. The spatially smoothed catalog seismicity and C-zones will fill in the rest of the bins. Let’s examine the simplest case of all of California: the fault-based models fill up many of the available magnitude bins, but the way they are filled will depend on whether a segmented characteristic model or some other approach is used. In either case, the background sources will fill the rest. The overall magnitude-frequency shape may follow a Pareto or other cut-off [e.g., Kagan and Schoenberg, 2001] but this should have little influence on the background if we assume that the A-faults and longest B-faults control the statewide overall Mmax.

Armed with the statewide magnitude frequency distribution, we can examine smaller regions in a systematic way because we have a zero-sum game. That is, there is only a limited supply of earthquakes of a given magnitude available, and if one region claims them, there are fewer available in others. Some subregions will be crossed by large faults that will claim larger magnitudes, leaving none available for the background, and some will not. Each of course will have its own Gutenberg-Richter distribution.

We start with an assumed grid of subregions across the state. We then look at all the areas crossed by major faults first. Projecting the subregional magnitude-frequency distribution to its zero crossing, and then subtracting off all the “taken” bins and partially filled bins by the fault-based rate models leaves the available higher-end bins. Subregional Mmax is then defined by the highest available bin. All this time we are also accounting for the state-wide limit. Once a statewide magnitude bin is full, that magnitude is not available for use anywhere else. We thus keep track of local magnitude bins and overall bins. The last areas we examine are those that are almost, or completely fault-free. There will be a small number of high-magnitude events left to apportion at this point but we will know exactly how many are left. We follow the same procedure as before by projecting the local a-value and b-value across the zero line for Mmax and develop a rank order. We then assemble the available earthquakes left in the statewide budget in rank order and assign them accordingly. We could just do this with the a-values and avoid the roll-off issue at the zero crossing.

Another source of input might be GPS-based strain rate mapping that can be used as an additional ranking mechanism. In this way higher strain rate subregions would get the biggest available magnitudes for Mmax. Presumably this result would mirror the rank-order assignment described above with the exception of short-term clustering in the smoothed background rates.

A final note about this process is that background Mmax will depend on whether the fault-based rate model is characteristic or not. This will govern the availability of different magnitudes to the background. Generally it is expected that a characteristic model will cause the background Mmax to be slightly smaller.

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Task R11: Focal Mechanisms of Off-Fault Seismicity

Task Leader: David D. Jackson (UCLA)

Introduction

Kagan, Jackson, and Rong [2007] employed a smoothed seismicity model to forecast earthquakes in California. The method is further described in Kagan and Jackson [1994]. The model is based on evaluating, at each map point, a weighted average of the number of earthquakes per unit time in the vicinity. Weights depend on the magnitude of the earthquakes and their distance from the map point. Their forecast included estimates of the moment tensors of future earthquakes, constructed by weighted averages, with the same weights, of the moment tensors of those nearby earthquakes. We would apply the same technique for all of California to estimate focal mechanisms, and their uncertainties, for all California.

Model Formulation

Our spatial smoothing kernels have the form

$$f(r) = A * (m - m_l) / \sqrt{r^2 + d^2}$$

Where A is a normization constant, r is the distance from a map point to an earthquake, m is the magnitude of that earthquake, m_l is the lower magnitude threshold for the catalog, and d is a constant, related to the uncertainty of location accuracy. For each earthquake, we normalize the moment tensor; then for each map point, we sum the moment tensors times the weight implied by the equation above. By normalizing the moment tensors of each earthquake first, we assure a magnitude weighting given by the equation above, which depends only mildly on magnitude. The variance of the focal mechanism parameters at a map point is determined approximately from the same weighted sum of the variances of the known earthquake focal mechanism.

However, the statistics of focal mechanism parameters is not Gaussian, so the error estimates are a bit complicated; details are given in Kagan et al. [2007] and references therein.

Input Data

The only input data needed are locations and focal mechanisms of earthquakes within about 100 km of the region of interest. We'll use a uniform lower magnitude threshold, determined by the smallest magnitude for which all events have measured focal mechanisms. We will not distinguish between on-fault and off-fault earthquakes; all are informative about the focal mechanisms, and there is no danger of double counting because we are only calculating the normalized focal mechanism.

Optional extension of the concept

It is relatively straightforward to include fault orientations and slip directions along with earthquake focal mechanisms as input data. We could convert earthquake occurrence to earthquake rate by dividing by the temporal length of the catalog, subdivide faults into sections, compute tensor moment rates for each section, and compute weighted averages in the same way we do for earthquakes. Some experimentation would be required, as the effective weight of each fault section would depend in a nonlinear way on its length.

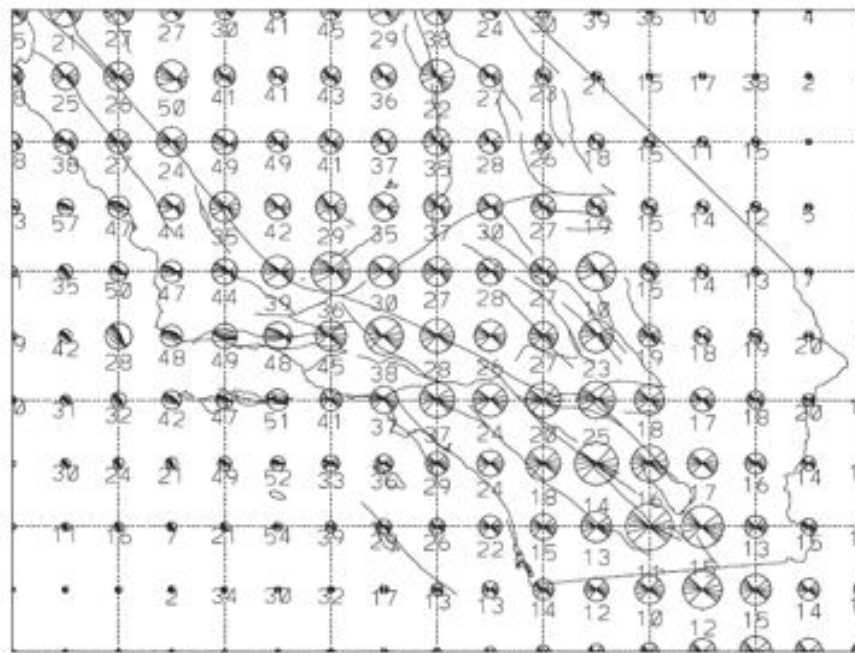


Figure 1. Long-term forecast diagrams of earthquake focal mechanisms in southern California. Lower hemisphere diagrams of focal spheres are shown. Size of the focal mechanism diagram is proportional to forecasted rate of occurrence (see figure 1). Stripes in beach balls are concentrated toward the assumed earthquake fault plane. The numbers below the diagrams of earthquake focal mechanisms correspond to a standard deviation of a weighted 3-D rotation angle. We first calculate the average seismic moment tensor and then compute the rotation of earthquake focal mechanisms with regard to the average double-couple source. Therefore the average rotation angle shows degree of tectonic complexity. Points without beach ball diagrams denote places for which data are inadequate to forecast focal mechanism. From Kagan et al., [2007]. The plot is displayed at URL http://moho.ess.ucla.edu/~kagan/s_cal_fps.ps.

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Task R12 – Distribution of Repeated Slip at a Site on a Fault

Task Leader: Ray Weldon (UO)

Statement of the Problem: The variability of slip at a site on a fault from earthquake to earthquake is a critical but hotly debated parameter. The characteristic earthquake model posits that repeated displacements are very similar, whereas other recurrence models produce less regular repetition of displacement.

Proposed Solution: We intend to collect a global dataset of both repeated historic ruptures and studies of prehistoric ruptures to assess how repeatable slip at a point on a fault is, and if possible understand what controls the variability if it varies from fault to fault. This effort will build on a number of existing summaries and will be a component of a larger effort to collect and interpret information of historic ruptures to assess fault-to-fault jumps, and distribution of slip along strike in ruptures and other parameters we seek to better understand.

Task R13 – Evaluate Physics Based Earthquake Simulators (for rate estimates)

Task Leader: Ned Field (USGS)

We would first want to convince ourselves that any given simulator is able to reliably reproduce the following (each of which is either imposed, or to some extent well constrained):

- long-term slip rates.
- paleoseismic event rates where available.
- magnitude-frequency distribution (MFD) for entire region.
- magnitude-area and/or slip-length scaling relationships.
- fault-to-fault rupture jumping distances (consistent with observations?).
- Omori decay, at least for small events.

Once a simulator has been “verified” in terms of consistency with the above, we might then want to examine any of the following:

- MFDs at points on faults (Characteristic or Gutenberg Richter?).
- MFD for entire “faults” (assuming faults can be meaningfully isolated and defined).
- Is one 1500-yr sample on a fault (like our SSAF paleo record) indicative of long term behavior?
- Can we run simulators long enough to constrain the long-term rate of “every possible” rupture (at some discretization level)?
- Recurrence-interval statistics at points on a fault, for faults, and for regions.
- Magnitude dependence of recurrence-interval statistics.
- Elastic-rebound predictability (time and/or slip predictable?).
- Sensitivity of large-event statistics to changes in cell size (e.g., in going from ~4 km cells to ~1 km cells).
- Multi-fault rupture behavior (what influences such occurrences).
- Average slip distribution along strike (e.g., is the average over many repeats of the same event broadly tapered (e.g., $\sqrt{\sin}$) as used in UCERF2) or more flat in the middle? What’s the variability about this average?.
- Does slip continue to penetrate deeper (below the depth of micro seismicity) for longer and longer ruptures?
- The rate of small earthquakes on faults (consistent on the large faults that seem quiet, like parts of the San Andreas?)
- Spatial-temporal clustering, especially for larger events (does ETAS apply at largest magnitudes?; is the fraction of “aftershocks” magnitude independent?).
- Longer-term time dependencies (like implied by the “empirical” model)?
- How do we glean applicable statistical rules from simulators for the purposes of hazard assessment (e.g., assuming a simulator is perfectly correct, how can we use it)?
- Robustness of all of the above with respect to different simulators and alternative parameter settings within a simulator (i.e., what are the epistemic uncertainties).

Task R15 – Cascadia Subduction Zone

Task Leader: Art Frankel (USGS)

Plans for Updating the Characterization of the Cascadia Subduction Zone for the National Seismic Hazard Maps and UCERF:

1. We will evaluate the recent results of Goldfinger et al. (2010) from turbidite data that show a recurrence time of about 230 years for M8 and larger earthquakes along the southern portion of the Cascadia subduction zone (CSZ). We are planning a small focused meeting of experts for Fall 2010 to assess the evidence for this higher rate and compare the turbidite results with onshore data, especially from Bradley Lake, Oregon.

2. Based on the results of this meeting, we will develop new magnitude-frequency distributions for Cascadia great earthquakes. These distributions may differ between the northern and southern portions of the CSZ. We will also assess whether multiple distributions should be used to quantify the epistemic uncertainty in recurrence model for any portion of the CSZ.
3. We will evaluate the possibility of temporal clustering of CSZ earthquakes that has been proposed by Goldfinger and Wong.
4. We will evaluate various models for the location of the eastern edge of the rupture zones for great earthquakes on the CSZ. Some scientists have suggested that the up dip limit of tremor events (ETS) may signify the down dip edge of the locked zone. This edge is similar to the geometries that were given substantial weight in UCERF2 and the 2002 and 2008 NSHMs. We will also evaluate recent work using GPS, tide gauge, and microfossil data that provides constraints on the location of the locked zone.
5. We will update the location of the plate interface based on the latest compilation by McCrory.
6. We will reassess our time dependent model for CSZ, which is based on the time since the 1700 earthquake. It remains to be seen how this can be combined with observations of a shorter recurrence time in the southern CSZ.
7. We will hold a regional Pacific Northwest workshop for the update of the NSHM in 2011. The CSZ issues noted above will be discussed at this workshop, so this workshop will also be important for UCERF 3.

Task P1 – Address Empirical Model

Task Leader: Karen Felzer (USGS)

Status of Model Components

The empirical model is the application of a reduction of the short term expected number of earthquakes based on observations that the recent, instrumental (post-1932) California catalog contains a lower seismicity rate than the 1850-2007 average. In UCERF2 the empirical correction was applied in region-specific amounts to all regions in the state for which sufficient data was available. Regions were drawn to encompass areas of similar levels of catalog completeness, where the latter was determined from the locations of population centers and newspapers and later seismic instruments, based on the methodology of *Schorlemmer and Woessner* (2008). The state as a whole is complete to only ~M 7.5 from 1850 (UCERF2, Appendix I), thus the use of different completeness regions is essential to calculating catalog-based seismicity rates.

Over the whole state the seismicity rate in the modern instrumental era is about 75% of the 1850-2006 average. Given difficulties in estimating the magnitudes and locations of historic

earthquakes, there is significant question regarding the robustness of the rate decrease. Recent seismicity rates are also low in comparison to GPS measurements, however. *Ward* (1998) estimated that the 1850-1996 rate of seismic moment release in California was only 75% - 86% of the long term geodetic-based rate. The average annual seismic moment release from 1932-2006 is about 60% of the long term geodetic rate estimated by *Ward* (1998). Thus re-evaluation of the catalog may allow for more precise determination of the rate difference, but there are multiple lines of evidence that the current seismicity rate is lower than the long term average. In fact, it can be shown with simulations that the clustering of most earthquakes in aftershock sequences means that the majority of the time the seismicity rate is expected to be below average. Important questions remain, however, about the cause of the rate reduction (see task 26 below). If it cannot be shown definitively that the cause is anything other than aftershock clustering then something like the ETAS model rather than a straight linear projection should be used to estimate how this rate reduction might play out in the future.

Research Plan

Re-calculate the rate change between the instrumental and full catalog after reassessment of the historic catalog (Task 17) using the methods, regions, and completeness thresholds given in UCERF2, Appendix I.

Error bars on the rate change for most regions were very high in UCERF2, and given the limited data are likely to remain high. We will investigate the implications of these large errors on the best course of action.

References

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Task P2 – ETAS explains Empirical Model?

Task Leader: Karen Felzer (USGS)

Current Status

UCERF2 demonstrated that a decrease in rate between the instrumental and historic catalog exists in all regions of California with the possible exception of the Mojave, which may have experienced a rate increase. The change appears strongest in the San Francisco Bay Area, where the rate decrease is on the order of 50% for 1906-2006 vs. 1850-1906. An iconic figure by Ross Stein (Figure 1, below) shows 14 $M \geq 6$ earthquakes in the 75 years preceding 1906 and 1 in the 75 years following 1906, an apparently dramatic shift in the seismicity rate. A similar plot,

known colloquially as the “tombstone plot”, shows 33 $M \geq 5.5$ earthquakes for 1850-1906 and 10 $M \geq 5.5$ earthquakes for 1906-2002.

Variations in seismicity rate are normally expected as a consequence of aftershock triggering. The majority of earthquakes occur as aftershocks (*Gardner and Knopoff, 1974*) and aftershock triggering can cause clustering to occur over a range of time scales. This variability can be modeled with the stochastic ETAS model (*Ogata, 1988*), although the model is limited because aftershocks of earthquakes too old, distant, or small to be in the earthquake catalog are not included, and because the magnitude of the smallest earthquake that can produce aftershocks is not known. As a result the model uses a steady background rate that is higher than the true rate, and outputs a lower limit on aftershock-related variability. Nonetheless, preliminary trials show that ETAS simulations can randomly produce $M \geq 6$ rate changes similar to that in the Stein figure, over similar times and areas (Figure 2). Whether ETAS can produce a coordinated seismicity rate decrease over a large part of the state, as found in UCERF2, still needs to be investigated.

An additional complication is that on closer inspection much of the statewide rate decrease is concentrated along the San Andreas system. Many more earthquakes occurred on or near the length of the SAF from 1855-1927 than from 1927-2000 (*Felzer and Brodsky, 2005*). This sharp localization of the rate decrease may not be reproducible by current ETAS modeling without the introduction of variation in local background rates. We note that such variability may not be real but may be needed because of the limitations of the ETAS model noted above.

Research Plan

We plan to run the ETAS model, in the form described by *Hardebeck et al., (2008)*, to test how well it reproduces the seismicity rate changes statewide and in the UCERF2 defined regions.

After the regional testing we plan to look at the San Andreas system and any other locations found to experience severe rate changes. If these changes cannot be reproduced with normal ETAS we plan to experiment with adding in localized background rate changes to see if we can better reproduce the catalog.

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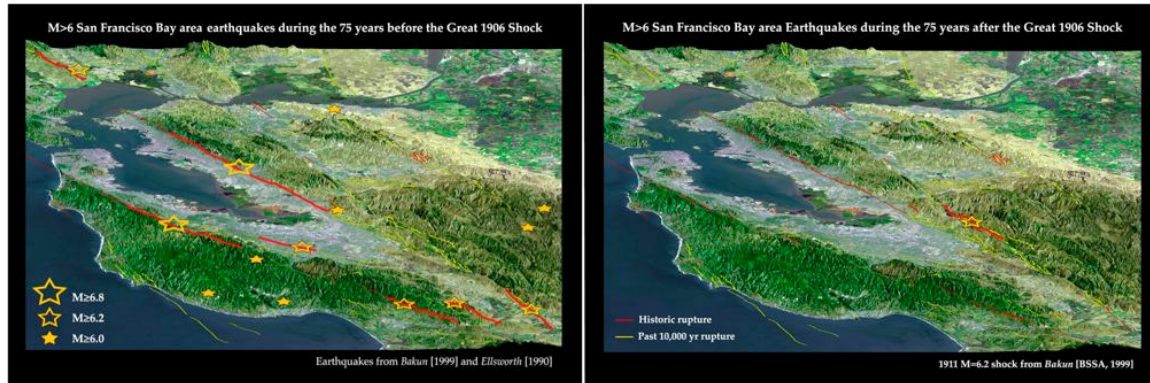


Figure 1. Iconic San Francisco Bay Area Shadow figure by Ross Stein

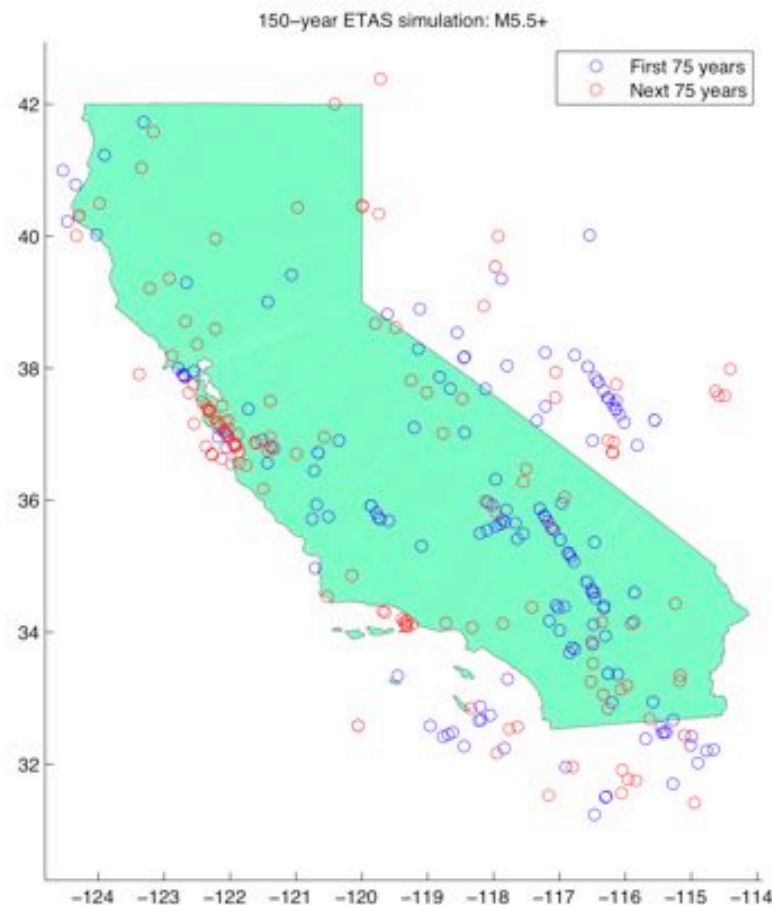


Figure 2: ETAS simulation of 150 year catalog. Note strong temporal rate changes in the San Francisco Bay Area and Mojave Desert.

Task P3 - Coulomb Stress Explains Empirical Model?

(also includes description of Task P7)

Task Leader: Tom Parsons (USGS)

Uncertainty about interactions led UCERF2 to avoid the issue altogether, concluding that the uncertainties in the rate model were larger than the interactions. UCERF2 instead adopted an empirical correction based on seismicity rate changes. Since we know that interactions do occur, this decision is not actually as conservative as it seems, particularly given the large influence of the empirical model, its considerable uncertainties, and arbitrary weighting in UCERF2. These two tasks are aimed at revisiting interactions, which have drawbacks (parameters), and advantages (physics, strong presence in the literature).

This task will proceed in concert with the reevaluation of the empirical model, and the historical earthquake catalog. Once we know what the observed rate changes are, and where large earthquakes occurred, we can readily prepare a statewide stress change map. The extent to which one explains the other will answer task P3. Postseismic mantle relaxation is not as exotic as it was in 1999, and thus can be defensibly (based on a decade of geodesy) incorporated into these calculations. While this adds parameters, these choices do not reverse the sign of the stress change, but tend to amplify the elastic calculations. Ideally we would have a physical basis for application of the empirical model, and importantly, gain insight into its application in areas of very large uncertainty.

Task P7 is asking whether Coulomb stress changes can be used along side empirical short-term forecasts like ETAS or STEP. Ideally one would get a spatial pattern of stress increase immediately after a mainshock. In practice, this has not worked well in prospective tests. Perhaps the best route would be to implement Coulomb calculations in parallel, but offline, to develop a database to compare with empirical methods and observed earthquake occurrence during the operational phase of UCERF3.

Tasks P5 & P6 - Implement ETAS for spatial-temporal clustering, and Evaluate the Agnew & Jones method

Task Leader: Andy Michael (USGS)

Earthquake clustering, in both space and time, provides a rare opportunity to forecast earthquake behavior over short time intervals with high probability gains compared to the probabilities of earthquakes occurring as independent events. Due to the high probability gains, these forecasts can be useful to society [*Michael et al.*, 1996]. Robust aftershock sequences can also produce significant probability gains for periods of years to decades. Estimating earthquake probabilities within clusters has been addressed by two substantially different approaches. Reasenberg and Jones [1989] combined two fundamental laws of statistical seismology, the Gutenberg-Richter distribution of earthquakes with respect to magnitude [*Gutenberg and Richter*, 1944] and the Modified-Omori law which describes the temporal behavior of aftershock sequences [*Utsu*, 1961] in order to estimate the probability of different magnitude earthquakes occurring during time-windows of an aftershock sequence. By extending their relationship above the magnitude of the initial event they also provided a model of foreshock behavior. The calculations in Reasenberg and Jones [1989] were corrected in Reasenberg and Jones [1994] and hereafter we refer to both of these papers as RJ89. The ETAS approach [*Ogata*, 1988] captures the same two fundamental laws and can be used in a similar way and has been applied to California by Felzer et al. [2003] among others. And the STEP model added spatial information to the RJ89 approach while also extending the results from probabilities to hazard [*Gerstenberger et al.*, 2005]. Agnew and Jones [1991] (hereafter AJ91) produced a model only of foreshock behavior by artificially separating earthquakes into four classes: aftershocks, mainshocks, foreshocks, and background events. The AJ91 method does not provide probabilities of aftershocks but provides a way to combine long-term estimates of earthquake probabilities into short-term estimates based on clustering.

Incorporating short-term time-dependent earthquake probabilities based on spatiotemporal earthquake clustering as part of UCERF3 requires selecting models that can be implemented in a manner that is consistent with the long-term UCERF3 probability models. The goal of having the short- and long-term methods be consistent is so that the total earthquake rates summed over independent events and sequences are consistent with the observations and that short-term forecasts of large events only include large earthquakes in areas where they can occur in the long-term model. Each of the models listed above has strengths and weaknesses. The RJ89 model is relatively simple but requires identifying sequences of earthquakes and producing probabilities for them. It has no spatial information other than the spatial definition of the sequence, which is arbitrary. A sophisticated approach to the spatial issue was added by the STEP approach but this approach still has the issue of identifying sequences that should be analyzed and included in estimating short-term probabilities. The ETAS approach avoids the problem of identifying sequences because each earthquake is considered as a source of its own aftershocks. A current limitation of all of these approaches is that they currently use a simple magnitude-frequency distribution that does not include characteristic earthquakes, which are present in the UCERF3 model. The AJ91 model does consider characteristic earthquakes and can include other magnitude-frequency distributions for the mainshocks. However, it is limited because it does not include aftershocks. In the case of simple magnitude-frequency distributions that cover the full range of earthquakes it has been shown that the AJ91 model reduces to the RJ89 model [Michael, 2010]. Thus, UCERF3's goal of operational earthquake forecasting will require a number of these models or a modification of one or more of them.

Initial plans are to attempt an implementation of the ETAS model that incorporates the spatially varying magnitude-frequency distribution of the existing UCERF2 model and which can be updated to the long-term component of UCERF3 when it is finished. This will ensure that large earthquakes will only be forecast where the long-term rate model allows them to happen. Questions here include: 1) how do we distribute the spatial component of triggering over the UCERF2 model. 2) should we compute temporally variable or sequence specific parameters?; 3) what should the lower magnitude limit be for updating the forecast based on observed seismicity; 4) will the fraction of main shocks versus triggered events be magnitude dependent? Our strategy will be to start with the simplest model and add complexity as needed to satisfy data or other constraints. For the AJ91 model we are determining if it adds additional, useful and meaningful information to the ETAS approach once the same magnitude-frequency distribution is used in both models. Depending on the results from these initial efforts we may need to combine the ETAS, STEP, and AJ91 models using a logic-tree. Given that STEP is based on the RJ89 model we do not expect to include the RJ89 model as a separate entity.

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Task P8 - Evaluation Other Time Dependencies

Task Leader: Jeanne Hardebeck

This section evaluates several spatial-temporal clustering behaviors that have been proposed in the literature, and not addressed in the previous sections of this report. Because there are tradeoffs between different forms of temporal clustering and variations this task will be coordinated with the other tasks on temporal variability in earthquake rates such as P1, P2, P3, P5, P6, and P7.

The recommendations from this section are:

- (1) It would be useful and feasible for UCERF3 to include earthquake swarms in operational earthquake forecasts.
- (2) ETAS models (Section 30) are most effective in successfully forecasting $M \geq 6.5$ earthquakes if smaller events, at least down to $M 3.0$, are incorporated into the forecasts. The strength of ETAS is in modeling multiple earthquake interactions within a catalog, rather than long-range or long-term triggering between large earthquakes.

- (3) The double-branching model, a long-term clustering added to the ETAS model to fit the global large earthquake catalog (*Marzocchi and Lombardi, 2008*), appears not to be applicable to California. Two independent studies have found that double branching does not improve upon the fit of the ETAS model to the California catalog. Additionally, there are some unresolved questions about the applicability of the double-branching model even to the global catalogs.
- (4) There is some evidence for mode-switching and/or coupling between various fault systems in California on very long time scales. However, these ideas have not yet been quantitatively developed to the point where they could be included in UCERF3, and it is unlikely that such long-term changes would have much affect on the relatively short-term UCERF3 forecasts.

Swarms

Although swarms are typically dominated by small-magnitude earthquakes, and UCERF is focused on the larger more damaging earthquakes, including swarm forecasts in UCERF3 would be beneficial to society in two different contexts:

- (1) An ongoing swarm in or near an urban area would be felt by many people and may cause property damage. A felt swarm would be a source of great concern for the affected community, and the public would be anxious to know what may happen as the swarm continues. An example is the 2008 Mogul swarm near Reno, Nevada (e.g. *Powers and Maugh, 2008*).
- (2) Swarms tend to occur near the Salton Sea, in proximity to the southernmost San Andreas Fault, which the UCERF2 report identified as the fault section most likely to fail in the next 30 years. Assuming that each earthquake in a swarm has some probability of triggering a San Andreas earthquake, the rate of earthquakes during the swarm must be forecast accurately in order to properly forecast the probability of triggering a southern San Andreas earthquake.

The temporal evolution of swarms differs from regular seismicity primarily in the greatly increased rate of spontaneous earthquakes, sometimes at rates thousands of times higher than usual (*Llenos et al., 2009*). This increase in the rate of spontaneous earthquakes is thought to be due to increased loading rate due to slow slip events or fluid movement. A stationary ETAS model would do a poor job of forecasting the rate of earthquakes in a swarm. Although a stationary ETAS model would accurately model the number of aftershocks from the events that have already occurred, it would vastly underestimate the number of new spontaneous events occurring during the forecast period. Therefore, swarm forecasts should be implemented by identifying the existence of a swarm, quantifying the rate of spontaneous swarm events, and temporarily updating the ETAS background rate accordingly. Implementing a swarm detection algorithm should be feasible within the time frame of UCERF3 (*Andrea Llenos, personal communication, 2010*).

ETAS and Double-branching.

A key question for operational earthquake forecasting in California is: If we build a stationary ETAS model based primarily on information from smaller earthquakes, will it successfully forecast the larger ($M \geq 6.5$) potentially damaging earthquakes that we are most concerned about? Work on the global catalog of large earthquakes has proposed that there is long-range, long-term clustering of large earthquakes that is not captured by the ETAS model alone, and that a second layer of clustering on ~ 100 km length-scales and ~ 30 year time scales is necessary. To this end, the double-branching model has been proposed (*Marzocchi and Lombardi, 2008*).

Preliminary work has shown, however, that the double-branching model is not needed in California, and that ETAS alone does a good job of fitting the California catalog. *Hardebeck (2010)* fit ETAS parameters to the UCERF2 instrumental catalog, which is dominated by smaller earthquakes. The combined historical and instrumental UCERF2 catalog of $M \geq 6.5$ earthquake was declustered using the same ETAS parameters, and no significant residual spatial-temporal patterns were found. Warner Marzocchi (personal communication, 2010) independently confirmed this result, showing that the double-branching model does no better than the ETAS model in explaining the California earthquake catalog.

The ETAS model for the UCERF2 $M \geq 6.5$ earthquake catalog has one unsatisfying feature. Some earthquakes that intuition suggests are connected - for example Landers following Joshua Tree and Hector Mine following Landers - are assigned a low probability of being triggered. The ETAS model is not modeling long-term, long-range triggering between large earthquakes; rather, these large earthquakes appear Poissonian. Large earthquake catalogs in general tend to contain little clustering (e.g. *Sornette and Werner, 2005*) and hence have limited usefulness for operational earthquake forecasting. Including smaller earthquakes in the ETAS model, and therefore more secondary triggering of large earthquakes, increases the clustering. If all earthquakes with $M \geq 3$ are included in the ETAS model, the Landers and Hector Mine events are identified as triggered. Similar results were found by *Felzer et al. (2003)*.

Another concern is that the California catalog of large ($M \geq 6.5$) earthquakes is quite short, and may contain too few earthquakes to identify subtle non-ETAS-like behavior with any statistical significance. Therefore, the failure to reject the ETAS null hypothesis is not a disproof of the double branching model. More work is required to further evaluate the double-branching model and its possible application to California. The double-branching model was developed on global datasets that encompass many different tectonic regions. A single set of ETAS parameters probably isn't appropriate everywhere, in fact *Zhuang (2010)* finds that even Japan can't be fit by a single set of ETAS parameter values. Forcing a single set of parameter values onto the entire globe may lead to poor fits in some locations, which appear as non-ETAS clustering. Additionally, the global catalog is dominated by subduction zone earthquakes. Assuming that double-branching reflects a real phenomenon, it is possible that it is related to the unique geometry of subduction zones and not applicable to most of California.

Long-term mode-switching and coupling

Paleoearthquake studies (e.g. *Rockwell et al.*, 2000; *Oskin et al.*, 2008) have shown that the earthquakes in the Eastern California Shear Zone (ECSZ) tend to cluster in time, with several fault systems producing large earthquakes within 1000-2000 years of each other, separated by >2000 years of few or no large earthquakes. Similar clustering has been identified in the Los Angeles area, out of phase with the ECSZ (e.g. *Dolan et al.*, 2007). Different hypothesis have been put forth, including mode-switching between the ECSZ and the Los Angeles area (*Dolan et al.*, 2007) and synchronization within the ECSZ due to stress-transfer coupling (*Scholz*, 2010).

These are intriguing results that should continue to be investigated. However, the mode-switching and coupling models currently exist as qualitative models, and have not yet been quantitatively tested. The lack of a quantitative framework also prevents these models from producing quantitative forecasts that could be incorporated into UCERF3. Additionally, given the very long time scales of this phenomenon, it is not clear that including it would alter the UCERF3 forecasts. For example, if we were to forecast the next 30 years based on the seismicity of the last 100 years and the geodetic deformation of the last 10 years, a ~1000 year cycle in the earthquake behavior would not be a large effect. The issue of mode-switching and coupling is part of the larger issue of reconciling geologic data, which samples long time-periods, with seismological and geodetic data, which samples the more recent past, and accounting for any differences in behavior at these different time scales.

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